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JOURNAL OF HUMAN SPORT AND EXERCISE

Volume 20, Issue 2 – April 2025

EDITED & PUBLISHED BY

ARD
ASOCIACIÓN ESPAÑOLA

ASOCIACIÓN ESPAÑOLA DE ANÁLISIS DEL RENDIMIENTO DEPORTIVO

ISSN 1988-5202

ORIGINAL ARTICLE

Factor analysis of the improvement of bat energy in baseball hitting

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ABSTRACT

Baseball hitting involves multiple biomechanical variables, and understanding their impact on bat energy is crucial for improving performance. However, no studies have explored how biomechanical features affect hitting performance from the perspective of bat energy. This study aimed to systematically investigate the influence of lower limb biomechanical variables on bat energy using factor analysis and stepwise regression methods. Sixteen right-handed baseball players participated in the study. Bilateral lower limb kinematic and kinetic features were calculated and exported using a motion capture system and force platform. Six key factors (F1–F6) were extracted from the 28 biomechanical features. Factors F1 and F5 are correlated with the rotation of the trailing and leading limbs, respectively; F2 correlates with energy production of the leading limb; F3 correlates with linear momentum production; F4 correlates with body posture control; and F6 correlates with body linear movement in the anterior direction. To enhance bat energy, hitters should step towards the incoming ball more rapidly to increase ground reaction force on the leading limb. They should also maximize extension and external rotation of both the leading and trailing limbs, stabilize the trailing limb during body rotation, and ensure proper weight distribution between the leading and trailing limbs.
Keywords: Biomechanics, Baseball biomechanics, Factor analysis, Baseball training, Baseball performance.

Cite this article as:
Yang, C., & Jin, P. (2025). Factor analysis of the improvement of bat energy in baseball hitting. *Journal of Human Sport and Exercise, 20*(2), 381-393. https://doi.org/10.55860/df8j1d03

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Submitted for publication September 15, 2024.
Accepted for publication November 07, 2024.
Published January 03, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/df8j1d03

INTRODUCTION

Baseball hitting is considered one of the most difficult skills to master in all sports. Hitters must accurately judge the timing and direction of their swing within a fraction of a second to successfully hit a baseball traveling at over 140 kilometers per hour. The question of how to achieve the maximum speed of a hit baseball has existed almost since the inception of the sport. Faster bat speed is strongly correlated with higher on-base rates and home run rates, making it a key factor in winning games (Horiuchi et al., 2024).

Some researchers have studied how to maximize bat speed. One study quantified the impact of shoulder, elbow, and torso movements on bat swing speed, finding a positive correlation between the moment of shoulder adduction/abduction and the angular velocity of torso rotation with bat speed (Koike & Mimura, 2016). This rotational force originates from the ground reaction force exerted by the feet, which hitters can use to increase the moment at the hip and knee joints, achieving faster torso and upper limb rotation (Ae et al., 2017). Additionally, since the ground reaction force of the leading limb is an important energy source for torso rotation (Howenstein et al., 2020), a larger stride will help increase the linear momentum during the step forward (Ramsey et al., 2014), and enhance the absorption of the ground reaction force by the leading limb, increasing the kinetic energy of torso rotation. Thus, greater extension of both lower limbs is also an important factor affecting hitting power. Howenstein used computer simulation to find that greater barrel-side shoulder abduction, knob-side elbow flexion, and torso right lateral flexion around ball impact can significantly increase bat swing speed from 36.5 to 40 m/s (Howenstein et al., 2020). These studies confirm that many kinetic and kinematic variables influence bat swing speed.

However, bat swing speed is only one factor affecting hitting power. Powerful swing requires transferring as much of the bat's energy to the ball as possible at the moment of contact. Specifically, the bat's kinetic energy is the sum of its translational energy, rotational energy, and potential energy. Translational energy is determined by the bat's mass and linear velocity, rotational energy is determined by the moment of inertia and angular velocity, and potential energy is determined by the bat mass, gravitational acceleration, and vertical displacement. These energies depend on the hitters ability to generate mechanical energy (Ae et al., 2020). During hitting, the greater the mechanical energy generated by the hitters body, the more energy is transferred to the bat per unit time, resulting in faster swing speed (Szymanski et al., 2010). Surprisingly, no researchers have directly examined the relationship between the mechanical energy of the bat and kinetic and kinematic characteristics. Moreover, the current problem in this field of research is that when researchers attempt to examine the relationship between a bat speed and several independent variables, they rely on their experience to select the kinematic or kinetic indicators (independent variables) to analyze. This is overly subjective and cannot comprehensively examine the relationship between all potential features and swing speed. Additionally, different studies may choose different features, resulting in non-complementary findings. Overall, theories on how to increase bat mechanical energy to enhance bat speed are fragmented. Previous studies have used factor analysis method to quantify key independent variables related to performance in cutting maneuvers and take-off performance in pole vaulting (Li et al., 2022; Welch et al., 2021). The advantage of this method is that it can include many independent variables at once, filtering out the truly useful ones through dimensionality reduction, and then performing regression analysis with the dependent variable. This comprehensively quantifies the correlation between independent and dependent variables, reducing the risk of bias from subjective selection of variables.

In summary, we collected kinetic and kinematic data from the leading and trailing limbs during a baseball swing. We then applied factor analysis for dimensionality reduction on the independent variables. After extracting the relevant factors, we conducted stepwise multiple linear regression analysis to explore the associations between these independent variables and bat energy during the swing.

METHODS

Participants

Sixteen right-handed baseball players participated in this study (age:23.6±2.4 years, experience: 7.8±1.5 years, height: 178.65 ± 3.11 cm, weight: 77.52 ± 13.21 kg). Each participant had been formally training for over six years. The inclusion criteria for the participants were as follows: male, accustomed to the automatic pitching machine, and maintaining regular training within the past six months. The exclusion criteria included having chronic or acute lower or upper limb injuries in the past three months, such as shoulder impingement syndrome, lumbar strain, knee osteoarthritis, and hip surgery. Each participant signed an informed consent form before the experiment, and the experimental procedures complied with the Helsinki Declaration. This study was approved by the Ethics Committee of Qufu Normal University (grant number: LL-20230009).

Procedures

The experiment was conducted in a rectangular area of approximately fifty m^2. Two force plates (sampling rate: 1000 Hz, model: BP600900, AMTI Inc, USA) were placed in the center of the field. Surrounding the field, a three-dimensional motion capture system consisting of 12 cameras (sampling rate: 200 Hz, model: Vantage V5, ox-ford Inc, UK) was set up. Before the formal test, 41 markers were attached to the subjects' bodies and 5 markers to the bat (Figure 1). The hitters then performed a static capture under the guidance of the experimenters. During the formal test, the subject's right leg (trailing limb) was positioned on force plate 1, while the left leg (leading limb) was on force plate 2. The leading limb is defined as the limb that steps towards the incoming ball during the hitting, while the trailing limb refers to the another limb (Lis et al., 2022). An automatic pitching machine (model:777BH, Furlihong Inc, China) was placed 16 meters directly in front of the subject, which launched fast baseball (weighing approximately 140 grams) towards the subject at a speed of 105 kilometers per hour. The subjects used a bat (model: B5 Pro, Easton Inc, USA) weighing approximately 850 grams to hit the baseballs, performing at least five effective hits.

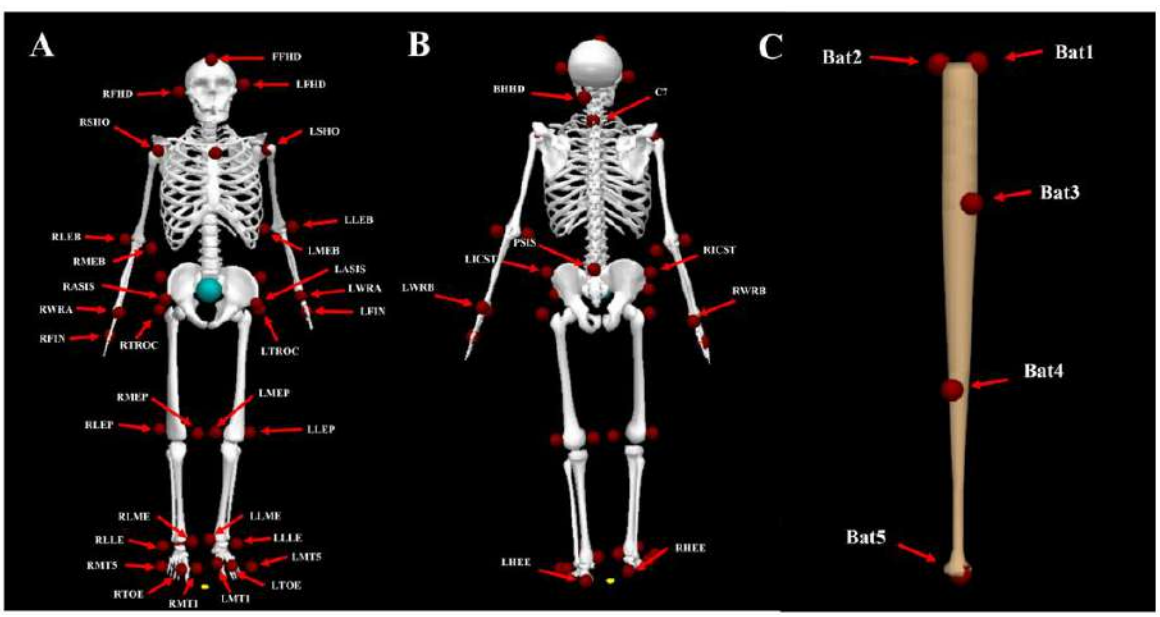

Figure 1. Marker protocol. A: front view. B: back view. C: marker placement in bat.

The force plates and the motion capture system were synchronized using a sync cable. The laboratory coordinate system was set as follows: the Y-axis represented the anterior-posterior direction, with the positive direction pointing towards the pitching machine; the X-axis represented the medial/lateral direction, with the positive direction being to the subject's back side (in the ready stance for hitting); and the Z-axis represented the vertical direction, with the positive direction pointing upward.

Data analysis

Each subject's static calibration file was imported into the Visual 3D biomechanical analysis system (version: V6 Professional, Has-Motion Inc, Canada). Based on the static files, a rigid body model of the human body and a rigid body model of the bat were established and saved as MDH format files. The model files were then applied to the motion capture files. The calculation method for bat energy is described in Equations (1) to (4):

$$M_{energy} = \mathrm{R}_{energy} + \mathrm{T}_{\mathrm{energy}} + \mathrm{P}_{energy} \quad (1)$$

In the above equation, M_{energy} is the Energy in the bat, R_{energy} is rotational energy of bat, $\mathrm{T}_{\mathrm{energy}}$ is translational energy of bat. P_{energy} is the potential energy.

$$\mathrm{T}_{\mathrm{energy}} = \frac{1}{2} * \mathrm{Mass} * (v_x * v_y + v_y * v_z + v_x * v_z) \quad (2)$$

In the above equation, Mass represents the mass of the bat, and v_x, v_y, v_z represent the bat's velocity components along the three coordinate axes, respectively.

$$\mathrm{R}_{energy} = \frac{1}{2}\mathrm{I}_{\mathrm{xx}}\omega_x\omega_x + \frac{1}{2}\mathrm{I}_{yy}\,\omega_y\omega_y + \frac{1}{2}\mathrm{I}_{zz}\omega_z\omega_z \quad (3)$$

In the above equations, ω_x, ω_y, and ω_z represent the angular velocities of the bat around the three coordinate axes, and I_{xx}, I_{yy}, and I_{zz} represent the moments of inertia of the bat around the three coordinate axes, respectively.

$$\mathrm{P}_{energy} = \mathrm{Mass} * 9.81 * COM_z \quad (4)$$

In the above equations, COM_z refers to the center of mass of the bat, which is approximately 52.6 cm from the handle along the longitudinal axis. Mass represents the mass of the bat.

Using function of "*LINK_MODEL_BASED*" in Visual3D, the following parameters was calculated: the joint moments of the bilateral hip, knee, and ankle joints; center of gravity (COG) speed at anterior[+]/posterior[-], medial[+]/lateral[-] and up[+]/down[-] direction; step length (distance between leading limb and trailing limb at foot contact);the ground reaction force components in the anterior[+]/posterior[-], medial[+]/lateral[-] and up[+]/down[-] directions from the two force plates. The anterior direction points towards the pitching machine, the medial direction points towards the subject's back (in the ready stance for hitting), and the superior direction points towards the sky. The calculations of joint moments was based on the Cardan Sequence, see Table 1, a standard method for representing joint motion recommended by the International Society of Biomechanics (Wu et al., 2005). All independent variables were processed using a zero-lag 4th-order low-pass filter with cutoff frequencies of 10 Hz for kinematic variables and 20 Hz for kinetic variables (Escamilla et al., 2009b), 30Hz for force plate data.

Table 1. Instructions of cardan sequence in this study.

Joint	Segment (Distal)	Segment (Proximal)	Sequence X	Sequence Y	Sequence Z
Ankle	Foot	Shank	PF [-]/DF [+]	EV [+]/INV [+]	ER [+]/IR [-]
Knee	Shank	Thigh	EXT [+]/FLE [-]	VAL [+]/VAR [-]	ER [+]/IR [-]
Hip	Thigh	Pelvis	EXT [-]/FLE [+]	ABD [+]/ADD [-]	ER [+]/IR [-]

Abbreviation: PF = Plantar flexion. DF = Dorsiflexion. EXT = Extension. FLE = Flexion. EV = Eversion. INV = Inversion. VAL = Valgus. VAR = Varus. ABD = Abduction. ADD = Adduction. ER = External Rotation. IR = Internal Rotation.

The swing phase was defined according to Shaffer et al.'s definition, where the beginning of this phase was marked by the end of the Wind-up and the end is marked by the moment of impact (Shaffer et al., 1993). Event detection commands were written in Visual 3D to accurately locate the start and end of the phase. For the phase start, the event tag was defined as the time point when the vertical ground reaction force exceeded 20N as the subject's stride limb stepped onto force platform 2. Since reflective markers were not attached to the ball, it was impossible to determine the exact time point of impact. According to previous research, the time point of contact usually occurs very shortly before the bat's resultant velocity reaches its peak (Mcintyre & Pfautsch, 1982). Therefore, in this study, the impact event was defined as the time point when the bat's resultant velocity reached its maximum value, with a backward adjustment of 30 milliseconds. All independent variable data within the swing phase were calculated, including the means, maximum, and minimum values, to be used for downstream analysis.

In this study, principal component analysis method was employed to perform dimensionality reduction on lower limb biomechanics features during hitting. This process yielded factors, which were subsequently iteratively incorporated into a linear regression model until convergence. Specifically, the linear regression model can generally be expressed by the following formula, where a_0 represents a constant, a_n denotes regression coefficients computed using the least squares method, and x_n represents independent variables:

$$Y = a_1 x_1 + \ a_2 x_2 + \cdots a_n x_n + \ \ a_0 \tag{5}$$

When incorporating the factors, the equation transforms into:

$$Y = \ a_1 * \ F1 + \ a_2 * F2 + \cdots a_n * F_n \tag{6}$$

Here, $\mathrm{F_n}$ encompasses a dataset of multiple independent variables transformed into a new dataset containing several uncorrelated factors, specifically:

$$F1 = \ a_{11} x_1 + \ \ a_{12} x_2 + \cdots \ a_{1n} x_n \tag{7}$$
$$F2 = \ a_{12} x_1 + \ \ a_{22} x_2 + \cdots \ a_{2n} x_n \tag{8}$$

Thus, incorporating factors into the regression equation provides linear regression coefficients between all independent variables and the dependent variable, without issues of multicollinearity among the independent variables. Therefore, we can obtain the correlation of each independent variable with the dependent variable (energy in the bat).

Statistical analysis

SPSS (version 26.0, IBM Inc., USA) was used for principal component analysis to obtain factors for dimensionality reduction of the independent variables. Subsequently, stepwise multiple linear regression analysis was conducted to examine the correlation between the reduced factors and the dependent variable (bat energy). The significance level for this study was set at $p < .05$

RESULTS

Table 2 shows the mean values of all features during the swing phase, based on data from 39 hits by 16 hitters.

Table 2. The descriptive data of the 28 features from 16 athletes.

Features	Mean	Std	Maximum	Minimum
Leading knee moment (Nm/kg)				
Extension	0.192	0.154	0.770	-0.291
Varus	-0.217	0.180	1.084	-0.344
External rotation	0.198	0.060	0.449	-0.028
Leading hip moment (Nm/kg)				
Extension	-1.011	0.375	-0.149	-2.589
Adduction	-0.115	0.154	0.559	-0.601
Internal Rotation	-0.287	0.105	0.031	-0.695
Leading ankle moment (Nm/kg)				
Plantar flexion	-1.023	0.196	-0.421	-1.926
Eversion	0.085	0.116	0.775	-0.105
External rotation	0.056	0.049	0.353	-0.080
Trailing knee moment (Nm/kg)				
Extension	0.112	0.166	0.646	-0.355
Varus	-0.455	0.137	-0.004	-0.956
External rotation	0.575	0.166	1.231	0.044
Trailing hip moment (Nm/kg)				
Extension	-0.661	0.281	0.706	-1.624
Adduction	-1.135	0.278	-0.163	-1.868
External rotation	0.426	0.115	0.894	-0.114
Trailing ankle moment (Nm/kg)				
Plantar flexion	-0.368	0.105	-0.027	-0.984
Inversion	-0.205	0.092	0.511	-0.521
Internal Rotation	-0.143	0.063	0.095	-0.324
Force plate contact by leading limb (N)				
Posterior	-337.521	83.249	-98.923	-584.039
Medial	151.917	37.795	280.863	30.278
Vertical	912.862	188.291	1697.592	321.643
Force plate contact by trailing limb (N)				
Anterior	57.701	30.522	110.559	-96.095
Lateral	-104.016	19.451	-22.469	-170.551
Vertical	284.460	44.023	494.436	139.878
Center of gravity speed (m/s)				
Anterior	0.691	0.092	1.056	0.373
Medial	0.081	0.064	0.426	0.095
Vertical	-0.067	0.096	0.295	-0.461
Step Length (m)				
Anterior	0.837	0.044	1.047	0.671

The Kaiser-Meyer-Olkin (KMO) score was 0.638, and Bartlett's test of sphericity was significant (p = .000), indicating that factor analysis was appropriate (Table 3). Therefore, dimensionality reduction was performed on the 28 independent variables, retaining only factors with eigenvalues greater than 1, with a maximum of 25 iterations, six principal component factors were extracted (Table 4).

Table 3. Bartlett's and KMO test results.

Bartlett's Test of Sphericity	**Value**
Approx. Chi-Square	1840.861
df	378
Sig.	.000
KMO Measure of Sampling Adequacy	0.638

Abbreviation: df = Degrees of freedom. Sig.: Significance; KMO: Kaiser-Meyer-Olkin.

Table 4. Total variance explained.

Component	**Initial Eigenvalues**			**Rotation sums of squared loadings**		
	Value	% of Variance	Cumulative %	Value	% of Variance	Cumulative %
1	10.878	38.848	38.848	6.371	22.753	22.753
2	4.477	15.989	54.837	4.729	16.889	39.642
3	3.451	12.327	67.164	4.598	16.421	56.063
4	2.982	10.651	77.815	3.976	14.199	70.262
5	2.033	7.261	85.076	3.424	12.230	82.492
6	1.312	4.684	89.760	2.035	7.268	89.760

The six factors explained 89.760% of the variance (Table 4), extracts these six factors is appropriate, because there are explained the most variances. The factors of F1 includes trailing limb ankle internal rotation moment (0.806), knee external rotation moment (0.918), and leading limb hip external rotation moment (0.890), F2 includes leading limb hip adduction moment (-0.812), ankle plantar flexion moment (0.844), vertical force (-0.826) and medial force (-0.828) from force plate contact by leading limb, F3 includes trailing limb knee (0.889) and hip (0.868) extension moment, F4 includes trailing limb ankle plantar flexion moment (0.884) and vertical force (-0.895) from force plate contact by trailing limb. F5 and F6 includes hip external rotation moment (0.952) of trailing limb and body speed (0.882) in anterior direction (Table.5).

Table 5. Rotated component matrix and communalities.

Features	**Component**					
	1	2	3	4	5	6
COG Speed Anterior	-0.647	-0.118	-0.027	0.435	0.191	0.882
COG Speed Medial	-0.207	0.031	0.323	0.698	0.399	0.220
COG Speed Vertical	-0.187	0.036	-0.006	-0.155	0.275	-0.442
FL Posterior force	0.185	0.712	-0.082	-0.443	0.068	0.424
FL Medial force	-0.414	-0.826	-0.036	-0.096	0.247	0.092
FL Vertical force	-0.207	-0.828	0.129	0.424	-0.094	-0.198
FT Anterior force	0.389	0.206	-0.353	-0.559	0.268	-0.420
FT Lateral force	0.647	0.449	0.405	0.012	-0.115	0.082
FT Vertical force	0.092	0.269	0.092	-0.895	-0.095	0.029
LA Plantar flexion moment	0.456	0.844	-0.149	-0.106	0.124	-0.305
LA Eversion moment	-0.312	-0.251	0.380	0.163	0.784	0.165
LA External rotation moment	-0.212	-0.221	0.746	0.179	0.479	0.071
Step Anterior length	-0.561	-0.085	0.109	0.645	0.030	-0.368
LH Extension moment	0.290	0.429	-0.508	-0.519	-0.284	0.253
LH Adduction moment	0.471	-0.812	0.182	-0.044	0.015	0.028

LH Internal rotation moment	0.890	-0.106	-0.027	0.025	-0.276	-0.075
LK Extension moment	-0.037	0.336	-0.747	-0.074	-0.093	0.193
LK Varus moment	0.046	-0.495	0.479	0.103	0.649	0.257
LK External rotation moment	-0.495	0.670	0.047	-0.089	-0.360	0.103
TA Plantar flexion moment	0.122	0.025	0.257	0.884	-0.018	0.026
TA Inversion moment	0.523	-0.155	-0.471	-0.219	-0.524	-0.139
TA Internal rotation moment	0.806	0.315	-0.206	-0.243	0.077	0.035
TH Extension moment	-0.311	-0.095	0.868	0.274	0.091	-0.100
TH Adduction moment	0.918	0.150	-0.270	-0.060	-0.107	-0.083
TH External rotation moment	-0.151	0.054	0.004	-0.002	0.952	0.019
TK Extension moment	-0.159	0.162	0.889	0.029	0.035	0.185
TK Varus moment	0.782	-0.016	-0.453	-0.130	-0.132	-0.187
TK External rotation moment	0.918	0.054	0.450	0.091	0.426	0.222

Abbreviation: LA = Leading limb ankle. LH = Leading limb hip. LK = Leading limb knee. TA = Trailing limb ankle. TH = Trailing limb hip. TK = Trailing limb knee. FT = Force plate contact by trailing limb. FL = Force plate contact by leading limb. COG = Centre of gravity.

The next step is conducting six factors were analyzed using stepwise linear regression to quantify the relationship between the independent variables and the dependent variable (Table 6), the R^2 of the model was 0.885, and the adjusted R^2 was 0.861. The observed F statistic for the significance test of the regression equation was 14.831, p = .001, therefore, the null hypothesis of the regression equation significance test should be rejected, indicating that the regression coefficient is not zero. A significant linear relationship was found between the explanatory variables and the dependent variable, confirming that the linear model is reasonable. The final regression equation is as follows:

$$Energy = -0.527 * F1 - 0.489 * F2 + 0.374 * F3 \ldots - 0.243 * F6 \quad (9)$$

Table 6. Linear regression analysis statistics of six factors.

Variables	Coefficient	Std. Error	t-Statistic	Prob
Constant	-2.8463E-16	0.062212	0	1.000
F1	-0.527	0.063	-8.347	.000
F2	-0.489	0.063	-7.754	.000
F3	0.374	0.063	5.921	.000
F4	0.325	0.063	5.155	.000
F5	0.252	0.063	3.992	.000
F6	-0.243	0.063	-3.852	.001
R-squared		.885	F-statistic	14.837
Adjusted R-squared		.861	Prob. (F-statistic)	.001

Table 7. Linear regression analysis statistics of six factors.

Features	Coefficient	Features	Coefficient
Leading knee moment		Force from plate contact by leading limb	
Extension	-0.518	Posterior	-0.706
Varus	0.531	Medial	0.617
External rotation	-0.194	Vertical	0.724
Leading hip moment		Force from plate contact by trailing limb	
Extension	-0.853	Anterior	-0.449
Adduction	0.199	Lateral	-0.454
External rotation	-0.471	Vertical	-0.467
Leading ankle moment		Center of gravity speed	
Plantar flexion	-0.588	Anterior	0.649
Eversion	0.639	Medial	0.363
External rotation	0.660	Vertical	0.151

Trailing knee moment		Step Length	
Extension	0.310	Anterior	0.684
Valgus	-0.604	Trailing ankle moment	
External rotation	-0.259	Plantar flexion	0.296
Trailing hip moment		Inversion	-0.546
Extension	0.671	Internal rotation	-0.723
Adduction	0.171	\	\
External rotation	0.289	\	\

Finally, substitute the factor scores of each independent variable from Table 4 into Equation 9, can calculate the correlation between each independent variable and the dependent variable (Table 7).

DISCUSSION

Achieving high-speed hitting is crucial for winning baseball games, and the energy contained in the bat plays a significant role in high-speed hitting. To our knowledge, no studies have comprehensively examined the correlation between lower limb biomechanics and bat energy. In this study, we introduced twenty-eight independent variables, covering nearly all measurable lower limb features during a baseball player's swing. We identified six distinct factors, each playing a unique role in the baseball swing. These findings will be discussed in detail below.

F2 responded for energy transfer between limbs. Results show that the plantar flexion moment of the leading limb ankle has a positive factor score but a negative contribution, while the adduction moment of the hip joint has a negative score but a positive contribution. This indicates that more plantar flexion moment is associated with reduced bat energy, whereas more adduction moment is linked to improved energy. The plantar flexion moment from the leading limb ankle at foot contact is well-documented (Ae et al., 2017). EMG studies have found that the gastrocnemius muscle activates approximately 500ms before ball impact and remains active for about 300ms (Nakata et al., 2013; Nakata et al., 2012). After the leading limb contact the force plate, the body needs to decelerate to transfer forward and vertical momentum to the pelvis and trunk, converting it into rotational components (Orishimo et al., 2023). When hitters move towards the incoming ball, the momentum and force from contact create an ankle dorsiflexion moment at foot contact. This causes the leading limb to move towards the ball's direction, leading to energy loss. Previous studies have shown that the plantar flexion moment plays an important role in decelerating the center of gravity speed during the gait cycle (Orendurff et al., 2008). Undoubtedly, the ankle plantar flexion moment during the swing phase helps hitters decelerate their body and avoid energy loss in this direction. However, the braking force must be carefully controlled, as excessive plantar flexion moment at the ankle can reduce the energy available for rotation. On the other hand, the results that greater hip adduction moment is helpful improving bat energy suggests that hitters should use the leading foot as a pivot when foot contact and control their lower trunk like a pendulum to generate more power during the swing. Previous studies have found that the adduction moment of the leading limb hip joint is the main power producer at swing phase (Ae et al., 2017).

Results show that the vertical force score is negative, but its contribution is positive, indicating that increased vertical ground reaction force from plate contact by leading limb is associated with improved bat energy. A previous study found that the peak vertical force could explain 38% of the variance in ball speed (Orishimo et al., 2023).We believe that hitters should employ a "*controlled fall*" mechanism, similar to pitching, to propel their bodies forward (Campbell et al., 2010). This mechanism accelerates the center of mass toward the leading limb, increasing velocity and incorporating more body mass into the batting motion, thereby producing more force compared to a direct step forward. Moreover, the medial force from plate contact by the leading limb has a negative factor score but a positive contribution, indicating that increased medial force is associated with enhanced bat energy. Note that in the force plate coordinate system, the medial direction points toward the back of the athlete. Medial force means more large energy for body rotational. According to Newton's third law, the medial and lateral force vectors are equal in magnitude but opposite in direction. During a golf swing, players shift their center of pressure (COP) to the trailing limb, activating the ankle eversion muscles to counterbalance the large moment created by ground reaction force (Choi et al., 2016; Marta et al., 2016). Therefore, to provide stable support for the leading limb, it is recommended that hitters use their ankle eversion muscles to generate a moment that stabilizes the foot and counteracts the ankle inversion moment caused by the medial force generated during the body's counterclockwise rotation.

All the variables in F1 have positive factor scores but negative contributions. These results suggest that increased internal rotation moment of the trailing limb ankle joint and external rotation moment of the knee joint are associated with reduced bat energy. When hitters begin to rotate their bodies, an increased internal rotation moment at the trailing limb ankle joint indicates that the foot is rotating internally along with the shank and thigh. If the foot were fixed to the ground and acting as a stable pivot, it would produce more external rotation moment, as the foot would remain stationary while the shank and thigh continue to rotate internally. If the foot undergoes internal rotation that exceeds the rotation of the shank or thigh, stability will be compromised, making it difficult to maintain stable support during rotation. Additionally, if the knee joint produces more external rotation moment during the rotation of the trailing limb, it suggests that the shank is rotating less than the thigh. If the shank were in sync with the thigh, the knee joint would be unlikely to produce external rotation movement. Without a doubt, the un synchronize of shank and thigh will disrupt the rotational rhythm and reduce energy production. Another interesting finding is that an increased internal rotation moment at the leading limb hip joint is correlated with reduced bat energy. Consider this: if the pelvis continues to rotate while the thigh remains stationary, it will create more internal rotational moment at the joint. However, this means the hip joint reaches its maximum external rotation limit faster, potentially leading to premature hip impingement (Sonnenfeld et al., 2021). At baseball pitching, pitcher leans forward to increase shoulder motion range before pitching, as a greater range of motion allows more time for acceleration (Stodden et al., 2005). Therefore, we suggest hitters rotate the thigh in coordination with the pelvis, or even surpass the pelvis's external rotation. This kind of movement strategy will result in a larger external rotation moment at the hip joint and produce more energy.

Another factor related to power production is F5. The results show that the factor scores and contributions are positive, indicating that increased external rotation moment of the trailing limb is correlated with higher bat energy. Baseball swing emphasizes a distal-to-proximal joint movement pattern, constructing the kinematic chain (Escamilla et al., 2009a; Welch et al., 1995). Therefore, these results suggest that the pelvis must rotate degrees should over pass the thigh of the trailing limb. Only then can the hip joint produce more external rotation moment. More pelvis internal rotation means more efficient trunk rotation, it will be helpful produced more bat energy.

F3 is related to the production and control of linear momentum, as all variables are activated in the sagittal plane. Results show that the factor scores and contributions are positive, indicating that increased hip and knee extension moments in the trailing limb enhance bat energy. During the rotation phase, the pelvis rotates nearly 90 degrees towards the incoming ball at a rate of 600-700 degrees per second. To achieve such a large rotation in such a brief time, the hip extensors of the trailing limb must generate significant mechanical energy. In the early phase of foot contact and body rotation, this energy mainly comes from the linear momentum generated by the contraction of the hip and knee extensors of the trailing limb (Liu et al., 2023) (Horiuchi & Nakashima, 2023). EMG studies have also shown that the hip extensor muscles peak in activation before the hitting event (Nakata et al., 2013). This linear momentum generates a large resultant moment at the pelvis, which applies angular acceleration to the trunk and upper limbs. The larger the resultant moment, the greater the angular acceleration of the trunk and upper limbs, and the greater the moment of inertia during the bat swing (Ae et al., 2017). The positive factor score and contribution for the center of gravity speed in the anterior direction indicate that greater speed in this direction is beneficial. These factors emphasize the importance of fully extending both the leading and trailing limb to generate more linear momentum and speed.

F4 is related to body posture control. Results show that the vertical force from plate contact by the trailing limb has a negative factor score and contribution, indicating that increased vertical force is correlated with a reduction in bat energy. A previous study found that the force from plate contact by the leading limb has a strong correlation with energy transfer to the trunk, while the force from the trailing limb does not (Horiuchi & Nakashima, 2023). Therefore, hitters should transfer more body mass to the leading limb. The positive effects of the trailing limb ankle plantar flexion moment on energy also suggest that transferring more body mass to the leading limb is beneficial. Additionally, the correlation between vertical force from leading limb contact and increased bat energy supports our speculation. However, we believe hitters should control their body mass distribution. Previous research has discussed the foot pressure of high-level and amateur hitters during hitting. High-level hitters typically shift their body mass to the leading limb at contact, but the trailing limb still maintains a reasonable portion (Moon et al., 2013). This is crucial for balance control. If hitters are unable to maintain their balance, it can cause instability in the bat's axis of rotation due to centrifugal force during the swing. Meanwhile, a balanced distribution of body mass will maintain the ideal position of COG between the COP of the trailing and leading limbs. This will helpful to creates more shear force against the ground and enhances pelvic rotation speed (Welch et al., 1995).

CONCLUSION

We used factor analysis and regression methods to explore the relationship between mechanical energy and 28 lower limb biomechanics features during baseball hitting, identifying six key factors. To enhance bat energy, hitters should step towards the incoming ball more rapidly to increase ground reaction force on the leading limb. They should also maximize extension and external rotation of both the leading and trailing limbs, stabilize the trailing limb during body rotation, and ensure proper weight distribution between the leading and trailing limbs.

AUTHOR CONTRIBUTIONS

All authors, Chen Yang, Pengfei Jin, have made substantial contributions to the conception and design of the work, the acquisition, analysis, and interpretation of data, and drafting or revising the manuscript. Each author has approved the final version to be published and agrees to be accountable for all aspects of the work. We also confirm that the manuscript has not been published elsewhere and is not under consideration for publication in any other journal. All co-authors have agreed to its publication in JHSE.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Levels of anxiety and self-confidence of Civil Guard motorcycle students at the traffic school in practice scenarios

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ABSTRACT

The aim of this study was to analyse the values related to the perception of anxiety and self-confidence shown by students of the motorcycle driving course at the Traffic Academy of the Guardia Civil. The study sample consisted of 31 subjects, Guardia Civil officers enrolled as students at the Traffic School. A specific test was designed to reflect different driving situations that challenged the subjects' skills. The tools used for data collection were the self-reported questionnaires: the State-Trait Anxiety Inventory (STAI-E) to measure state-trait anxiety and the Competitive State Anxiety Inventory-2R (CSAI-2R) to assess participants' pre-competitive anxiety. The statistical analysis showed differences in relation to the variables of cognitive anxiety, somatic anxiety, and state anxiety, considering the moments both prior to and after the driving test, as well as at the baseline moment. The correlation between all study variables and the different recording moments showed significant differences in most cases, with pre-test cognitive anxiety showing the least significance. The results of this study highlight the complexity of the interactions between anxiety and self-confidence in such specific evaluative contexts. This suggests the need to continue developing evaluation procedures and tests adapted to the idiosyncrasies of this group, which are crucial for the development of intervention programs that strengthen self-confidence, foster a positive mental state, and reduce anxiety in the subjects.

Keywords: Stress, Evaluation, Performance, Driving.

Cite this article as:
Moyano-Galán, M., Villafaina, S., & Fuentes-García, J. P. (2025). Levels of anxiety and self-confidence of Civil Guard motorcycle students at the traffic school in practice scenarios. *Journal of Human Sport and Exercise, 20*(2), 394-408. https://doi.org/10.55860/ysv24w09

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Submitted for publication October 07, 2024.
Accepted for publication November 29, 2024.
Published January 03, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/ysv24w09

INTRODUCTION

From the demands of the sports field, anxiety is defined as an emotional response to a perceived threat, combining physiological arousal and cognitive concerns (Smith & Smoll, 2004). In a competitive environment, a distinction can be made between trait anxiety, which is a relatively stable personality characteristic (Martens, 1977), and state anxiety, which refers to the symptoms that arise during a specific competition (Simon & Martens, 1979). Cognitive anxiety manifests through negative expectations about success or self-evaluation, negative thoughts, loss of self-esteem, self-criticism, fear of failure, low self-confidence, concerns about performance, images of failure, difficulty concentrating, and disrupted attention (Martens, Vealey & Burton, 1990; Jarvis, 2002).

On the other hand, somatic anxiety is related to autonomic arousal, such as increased heart rate or muscle stiffness, and can lead to negative symptoms such as nervousness, difficulty breathing, high blood pressure, dry throat, muscle tension, accelerated heart rate, sweaty palms, and a sensation of butterflies in the stomach (Martens, Vealey & Burton, 1990; Jarvis, 2002; Jones, 2000).

Self-confidence, which refers to individuals' belief in their ability to control themselves and their environment (Martens, Vealey & Burton, 1990), is also examined within this construct as a component that evaluates athletes' overall perceptions of achievement (Craft, Magyar, Becker et al., 2003). For example, tennis players experience a physiological response to anxiety characterized by the activation of the sympathetic nervous system (via the hypothalamus), which increases heart rate, dilates coronary arteries, constricts abdominal arteries, dilates pupils and bronchial tubes, strengthens skeletal muscles, releases glucose from the liver, enhances mental activity, dilates arterioles in skeletal muscles, and raises basal metabolic rate (Greenberg, 1999). Thus, studying cognitive anxiety, somatic anxiety, and self-confidence before competition provides valuable insights into athletes' pre-competitive anxiety (Cox, Martens & Russell, 2003).

In line with the aforementioned, previous studies have shown that, in different military contexts, situations of extreme psychophysiological demand can be observed, similar to those in high-performance sports and physical activity (Delgado, Robles, Aznar, & Clemente, 2019; Díaz, Fuentes, Fernández, Aznar, & Clemente, 2018; Hormeno & Clemente, 2019; Vicente, Fuentes, & Clemente, 2020; Vicente, Gallego, Fuentes, & Clemente, 2020).

In sports, competition plays a crucial role in the athletic ecosystem, affecting all participants in multiple ways (Koning, 2009). For athletes, regardless of their performance level, this specific situation generates both positive and negative experiences and emotional states, which depend on how they perceive and interpret the event, its significance, and its consequences. Anxiety is one of the most common experiences in this context (Smith, 1989).

In relation to the above, a previous study has highlighted the need to generate new knowledge on the management of psychophysiological load in sports (Fuentes, Villafaina, Mas, & Martínez, 2023). For instance, a study conducted with elite junior tennis players showed significant differences in cognitive anxiety, state anxiety, and self-confidence when comparing pre- and post-match values between winners and losers (Fuentes, Villafaina, Martínez, & Crespo, 2023).

Similarly, in the context of the physical and psychophysiological demands, as well as the stress control required of fighter pilots in the Air Force, a recent study on combat pilots (Hormeno & Clemente, 2019) demonstrated how the human body can reach certain limits in the context of aerial combat, as well as the effects on reducing cognitive anxiety and other impacts on lower limb strength levels. In both offensive and defensive manoeuvres, the results indicated a significant increase in Heart Rate (HR), perceived exertion (RPE), and stress. The study concluded that, given these findings, the high physical and psychophysiological demands underscore the critical need for specific training programs for combat pilots.

Additionally, combat pilots in the Air Force have been analysed for stress-related responses, including autonomic modulation (Delgado, Robles, Aznar, & Clemente, 2019). Important aspects such as the measurement of stress before and after using a flight simulator and real flight have also been examined using instruments like the Vienna Test System (VTS) (Schmidt, 2007). The results have shown it to be a useful objective measure of several psychological constructs, complementing existing subjective measures and increasing the predictive validity compared to self-reports (Ong, 2015).

In the Air Force, flight simulators have been used as a cost-effective and safe tool for pilot training, providing a simulated environment that replicates real-world conditions (Gerathewohl, 1969). To analyse the transfer of skills between simulator training and actual flights (Dahlstrom & Nahlinder, 2009), previous research has employed various psychophysiological tools to examine the cognitive demands of both types of flights (Wilson, 2002; Alaimo, Esposito, Orlando, & Simoncini, 2020). This is a crucial issue, as the abilities required for such flights demand high levels of cognitive load (Dahlstrom & Nahlinder, 2009; Wilson, 2002; Magnusson, 2002), making the assessment of mental workload a key aspect.

A recent study on fighter pilots focused on evaluating how autonomic response, anxiety, perceived exertion, and self-confidence manifest during real flights compared to simulated flights. The first hypothesis proposed that "*the impact of acute effects (on heart rate variability and anxiety) would be greater in real flights than in simulations*". To assess the participants' pre-competitive anxiety, the Spanish version of the Competitive State Anxiety Inventory-2R (CSAI-2R) (Cox, Martens, & Russell, 2003; Andrade, Lois & Arce, 2007) was used. This questionnaire consists of 17 items that measure cognitive anxiety, somatic anxiety, and self-confidence. Additionally, the State-Trait Anxiety Inventory (STAI-E) (Spielberger et al., 1971) was employed to measure momentary anxiety, consisting of 20 items. The STAI-E score ranges from 20 to 80, where a higher score indicates a greater level of anxiety (Spielberger et al., 1971). Perceived exertion was also evaluated using the Rate of Perceived Exertion (RPE) scale, which ranges from 6 to 20 (Borg, 1970).

Following the findings from a study conducted on Air Force paratroopers, within the context of the Armed Forces and the State Security Forces, the use of the CSAI-2R scale has been deemed a valid and reliable model for diagnosing anxiety in physical activities, competitions, or sports with very particular and special characteristics, such as military parachuting. This activity presents very specific conditions compared to others, due to its context and idiosyncrasies, as well as the peculiarities that define the group to which they belong (Borrego, Ortín, Zurita, Díaz, & Morales, 2024).

However, in light of the aforementioned findings that highlight the high psychophysiological demands on military personnel and the importance of implementing specialized training programs to reduce professional risk and enhance the quality of their performance, we have found no evidence based on a review of the major scientific publication databases that the training process for members of the Civil Guard Traffic Division has been analysed. Furthermore, we have found no studies comparing psychophysiological responses between novices and experts, for example, during motorcycle driving, to observe potential differences between the two groups that could assist instructors in developing specific and individualized training programs. These programs would be of the highest quality, grounded in objective data supported by scientific studies.

The Civil Guard is a State Security Corps that, in accordance with the Spanish Constitution, is assigned the general mission of "*protecting the free exercise of rights and freedoms and ensuring public safety*." This mission is carried out by guaranteeing public security and assisting citizens, aiming to provide an effective and reliable police response that contributes to a sense of safety (Ministry of the Interior, Government of Spain).

Among the specializations, understood as the "*Set of capabilities that enable Civil Guard personnel to perform specific functions in particular areas of activity within units or organic positions within the Civil Guard structure, for which one or more specific qualifications are required*", is the Traffic Division. Its mission is the monitoring, regulation, assistance, and control of traffic and transportation, ensuring road safety on interurban roads, as well as addressing potential threats to the public. The firm commitment to performing these functions inevitably exposes them to situations that generate uncertainty and stress. Therefore, it is important to highlight the risks associated with duty performance, the diversity of tasks and scenarios, emotional burden, time pressure, administrative and bureaucratic challenges, exposure to trauma, and social expectations, among other stressors. The requirement for a high degree of concentration, cognitive skills, and decision-making under pressure makes it essential that Traffic Civil Guard agents have effective strategies for managing stress and maintaining optimal performance in all situations. In this regard, it is of utmost importance to address and manage stress through programs related to stress management training, not only for the operational improvement of the Unit but also for the health and quality of life of the individual (Ministry of the Interior, Government of Spain).

In this regard, Civil Guard officers also have the same automatic survival programs; however, these are subject to specific stressors inherent to the profession, along with ambiguous regulations regarding the use of force and firearms. To effectively balance all these variables in their professional duties, solid theoretical and practical training is necessary, in which self-control techniques are essential (Soto, 2020).

Currently, the importance of developing didactic methodologies related to multilateral training, adapted to law enforcement, is evident. This is an extremely effective tool for fostering and improving both the physical and psychological condition of individuals, as well as their overall quality of life. Additionally, it provides important resources related to the prevention of occupational stress for these members. A specialized physical education program is also strongly recommended, specifically designed for police officers, which should be tailored to the specific training tasks required for each job position (Fischetti, Cataldi, Latino, & Greco, 2019).

The objective of the study is to explore stress management among students of the Civil Guard Traffic School during motorcycle driving and piloting in emergency situations, simulating scenarios of uncertainty and physical demands. Accordingly, the following hypotheses are proposed:

1. **Cognitive Anxiety:** The first hypothesis proposes that there will be a significant increase in cognitive anxiety during the pre-test and in situations of stress and uncertainty while riding a motorcycle, compared to the post-test results.
2. **Somatic Anxiety:** The second hypothesis suggests that there will be a significant increase in somatic anxiety during the pre-test compared to baseline results, as well as a significant increase in the post-test during situations of stress and uncertainty while riding a motorcycle.
3. **Self-Confidence:** The third hypothesis to be established is the increase in self-confidence values in the basal situation, with respect to the pre-test and post-test. Likewise, this will be higher in the post-test than in the pre-test.
4. **State Anxiety:** The fourth hypothesis suggests that there will be a significant increase in state anxiety during the pre-test compared to baseline and post-test results. Likewise, there should be a

significant increase between the post-test and baseline in situations of stress and uncertainty while riding a motorcycle.

5. **Age of the participants:** The fifth hypothesis states that older participants will have more self-confidence than younger ones before the start of the driving test.
6. **Time holding a driving license:** The sixth hypothesis suggests that participants who have held their driving license for a longer period will have more self-confidence before the start of the driving test than those who have had the document for a shorter period.
7. **Self-taught daily driving practice:** he seventh hypothesis proposes that the level of anxiety and self-confidence of subjects who practice driving more days per week (high-frequency practice group) will show lower levels of anxiety and higher levels of self-confidence compared to subjects who practice driving fewer days per week (low-frequency practice group).
8. **Correlations between variables:** In the eighth hypothesis, it is expected that the values of cognitive and somatic anxiety, as well as state anxiety (STAI-E), will present significant positive correlations throughout the different moments of measurement (baseline, pre and post). On the other hand, self-confidence will also show significant negative correlations with cognitive and somatic anxiety, and with state anxiety.

MATERIAL AND METHODS

Participants

A total of 31 students of the motorcyclist's course in the traffic specialty at the traffic school of the civil guard took part in this cross-sectional study. The students had a mean age of 32.39 (6.17) years. Participants weighed 78.87 (8.67) kg and heighted 176.93 (5.71) m. A total of two women (33.00 ± 4.24 years) and 29 men (33.41 ± 6.33 years) participated. Research procedures were approved by the University ethics committee (approval number: 50/2024). Students agreed to participate in this study by giving written consent.

Table 1. Characteristics of students of the motorcyclists course in the traffic specialty at the traffic school of the civil guard in the sample.

Variable	**Mean (SD)**
Age (years)	33.39 (6.17)
Height (cm)	176.93 (5.71)
Weight (kg)	78.87 (8.67)
Body Mass Index (BMI); (kg/m^2)	20.58 (1.92)
Months of validity of the motorcycle driving permit	100.16 (71.33)
Days per week you have used the motorcycle during the last year	1.87 (2.16)

Procedure

Participants were evaluated before and after the driving test, which was specifically designed and standardized for this purpose. The circuit designed for the test included challenging manoeuvres and difficulties associated with potential real-life situations they might encounter in their future professional careers. In no case where they provided with or given information about the circuit's configuration or the type of manoeuvres and skills to be performed. This information was given moments before the start, just prior to completing the circuit.

The circuit consisted of a route lasting between 12 and 15 minutes, which was divided into four sections. **Section 1)** Over 150 meters, participants had to manoeuvre in a zig-zag pattern around cones at different speeds (30, 50, and 70 km/h). The distance between the cones was 5, 7, and 10 meters, respectively.

Section 2) Consecutive circles in the shape of an 8 configured with signalling cones. This manoeuvre had to be performed by first turning towards the dominant side and then towards the non-dominant side, linking five consecutive sequences. The diameter of each circle was 4 meters, and the distance between their centres was 6 meters. **Section 3)** Riding on a dirt track. Here, they had to face several technical difficulties without putting their foot on the ground. **Section 4)** Riding on an asphalt road where they had to travel at high speeds (100 km/h), aiming for the correct entry into curves, accelerating properly once past the challenging part of the route, and ending with decelerating the motorcycle and riding in a standing position for a stretch of 70 meters, during which they had to manoeuvre in a zig-zag pattern through a line of cones at speeds below 10 km/h.

Anxiety and self-confidence were assessed both in a baseline state after a rest period away from the test day, as well as immediately before and after completing the circuit. Under no circumstances did the participants take any medication, stimulant drinks, or other substances that could affect their nervous system 24 hours before taking the test.

Instruments
The Competitive State Anxiety Inventory - 2R (CSAI-2R) (7) was utilized to evaluate the participants' pre-competitive anxiety. This instrument is widely recognized for analysing these variables within sports contexts (29). It has been specifically employed with competitive athletes (28) and in other high-stress environments such as those experienced by fighter pilots (30). Version of Spanish (31) was used for Civil Guards. All participants confirmed their comprehension of the tool and their comfort in providing responses.

The questionnaire comprises 17 items designed to measure cognitive anxiety, somatic anxiety, and self-confidence. Each item is rated on a 4-point Likert scale, ranging from "*not at all*" to "*very much so*". The Cognitive Anxiety subscale, which assesses negative feelings about performance and its consequences, includes 5 items, with scores ranging from 5 to 20 points. The Somatic Anxiety subscale consists of 7 items that address physiological indicators of anxiety, such as muscle tension, increased heart rate, sweating, and stomach discomfort, with scores ranging from 7 to 28. Additionally, the inventory features a self-confidence subscale, which evaluates the athletes' confidence in their competitive success, using 5 items that provide scores between 5 and 20.

Anxiety was also measured using the State-Trait Anxiety Inventory (STAI-E) (34), which examines anxiety phenomena through two scales: A-Trait (A-T) and A-State (A-S), each consisting of 20 items. The 40-item questionnaire employs a Likert scale from 0 (almost never) to 3 (almost always). The A-T scale reflects a relatively stable propensity to perceive situations as threatening, influencing the A-S. The A-S scale captures a transient emotional state characterized by subjective feelings of tension and apprehension, along with autonomic nervous system hyperactivity, which varies over time. Scores are calculated by subtracting the negative scale from the positive scale and adding 30 to the result. It is noteworthy that in the Spanish version of the STAI used in this study, the response scale was modified from the original 0-4 to 0-3, affecting only the mean values (reduced by 20), with the adjusted values plus 30 points included here. This modification did not impact other statistics (standard deviation, reliability, correlation indices), allowing for direct comparison. The test scores range from 0 to 60, with higher scores indicating higher levels of anxiety (34).

Statistical analysis
Statistical analysis was performed using SPSS software (Statistical Package for the Social Sciences, version 25 for Windows, IBM Corporation, Armonk, NY, USA). Based on the Shapiro-Wilk test results, non-parametric tests were applied.

To assess the internal consistency of the questionnaires, a reliability analysis was conducted using Cronbach's alpha, with a threshold of .70 or higher (35). Additionally, the omega coefficient (36) was utilized to verify the internal consistency of the variables. According to some researchers (37), the omega coefficient provides evidence of greater accuracy. The range for the McDonald omega coefficient is between 0 and 1, with higher values indicating more reliable measurements. Campo-Arias and Oviedo (2008) suggest that a confidence value greater than .70 is necessary for the omega coefficient to be considered acceptable.

The Friedman test was used to examine differences between baseline, pre-competition, and post-competition measurements. Pairwise comparisons were then conducted using the Wilcoxon signed-rank test, with Bonferroni corrections applied for multiple comparisons. Additionally, Kendall's W effect sizes [r] were calculated and categorized as follows: <0.1 as a small effect, between 0.1 and 0.5 as a medium effect, and >0.5 as a large effect (39,40).

Furthermore, a bivariate correlation analysis was conducted using Spearman's correlation coefficients to study the relationships between psychological profile and perceived stress variables.

RESULTS

The mean of cognitive anxiety, somatic anxiety self-confidence and state anxiety are shown in Table 2. Our findings demonstrate that the questionnaires exhibit an adequate level of internal consistency, with Cronbach's alpha and McDonald omega coefficients for all variables being equal to or exceeding 0.70. High values of internal consistency were found in all variables, being in all cases greater than 0.80.

Table 2. Descriptive statistics and reliability analysis.

Variables	N	Minimum	Maximum	M	SD	α	ω
Cognitive anxiety	31	1.00	4.00	2.09	0.77	0.83	0.85
Somatic anxiety	31	1.00	3.57	1.76	0.66	0.89	0.90
Self-confidence	31	2.20	4.00	3.74	0.51	0.87	0.88
State anxiety (Positive scale)	31	0	1.90	0.63	0.51	0.85	0.87
State anxiety (Negative scale)	31	0.50	3.00	2.50	0.45	0.87	0.86

Note. M: Mean, SD: standard deviation, α: Cronbach's alpha, ω: omega coefficient.

Table 3. Differences in the cognitive anxiety, somatic anxiety, self-confidence and anxiety state variables at baseline, pre-test, and post-test.

Variables	Baseline Mean (SD)	Pre-Test Mean (SD)	Post-Test Mean (SD)	*p*-value	Effect Size	Pairwise comparisons
Cognitive anxiety	2.07 (0.79)	2.23 (0.78)	1.95 (0.74)	.010*	0.15	B>C = 0.016*
Somatic anxiety	1.65 (0.54)	1.99 (0.68)	1.68 (0.63)	.002**	0.20	B>A = 0.010* B>C = 0.028*
Self-confidence	3.77 (0.34)	3.72 (0.41)	3.72 (0.42)	.826	0.01	
State anxiety trait (Total)	7.03 (6.27)	15.81 (9.15)	10.97 (9.04)	<.001**	0.44	B>A = <0.001** B>C = 0.033* C>A= 0.033*

*Note. A: Baseline; B: Pre-Test; C: Post-Test; SD: Standard Deviation; STAI-E A-S: State Trait Anxiety Inventory A-State; * p-value < .05: ** p-value < .01.*

The results obtained, as can be clearly seen in Table 3, reveal that the values of state anxiety, cognitive anxiety, and somatic anxiety were significantly higher before the driving test (B) than after it (C). Likewise, both the recorded values of somatic anxiety and state anxiety were significantly higher in the pre-test (B) than those obtained in the baseline measurement (A). Similarly, state anxiety showed significantly higher values at the time of the post-test (C) compared to those obtained in the baseline (A). Regarding the values related to self-confidence, no significant differences were recorded.

On the other hand, the study variables were also analysed with respect to the differences in age, length of time the motorcycle license has been in circulation and daily practice of self-taught driving, showing below only those results where there were significant differences. Regarding the pre-test Self-confidence variable and in relation to the participants' age, there are significant differences between the 30-39 age group (3.59) and the ≥40 age group (3.97). This variable also showed significant differences between the Civil Guards who obtained their license less than 60 months ago (3.98) and those who obtained it between 60 and 119 months ago (3.49).

Lastly, differences were observed in pre-test State Anxiety between those who have practiced four or more days (20.86) and those who have practiced between one and three days (10.20).

Table 4. Correlations between the baseline, the pre- and post-test values of the variables related with cognitive anxiety, somatic anxiety, self-confidence and anxiety state.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Cognitive anxiety baseline	1											
Somatic anxiety baseline	.53**	1										
Self-confidence baseline	-.53**	-.64**	1									
STAE-E baseline	.49**	.70**	-.61**	1								
Cognitive anxiety pre	.77**	.22	-.20	.24	1							
Somatic anxiety pre	.57**	.71**	-.56**	.55**	.32	1						
Self-confidence pre	-.64**	-.56**	.66**	-.55**	-.39*	-.60**	1					
STAE-E pre	.36*	.48**	-.43*	.45*	.23	.61**	-.55**	1				
Cognitive anxiety post	.79**	.26	-.27*	.39*	.85**	.45*	-.48**	.22	1			
Somatic anxiety post	.36*	.37*	-.37*	.51**	.17	.69**	-.44**	.37*	.31	1		
Self-confidence post	-.36*	-.36*	.41*	-.45*	-.23	-.27	.52**	-.51**	-.25	.29	1	
STAE-E post	.53**	.36*	-.50**	.58**	.42*	.69**	-.56**	.50**	.52**	.76**	-.39*	
M	2.07	1.65	3.77	7.03	2.23	1.99	3.72	15.81	1.95	1.68	3.72	
SD	0.79	0.54	0.34	6.27	0.78	0.68	0.41	9.15	0.74	0.63	0.97	
N	31	31	31	31	31	31	31	31	31	31	31	

Note. * $p < .05$; ** $p < .01$.

Table 4 shows the results of the correlations between the study variables. These are: state anxiety, cognitive anxiety, somatic anxiety and self-confidence at the different recording moments. Both at baseline, as well as before and after the driving test. There was correlation in the great majority except for the following correlations: Basal state anxiety and pre-test cognitive anxiety; -Pre-test state anxiety and post-test cognitive anxiety; -Pre-test cognitive anxiety and somatic anxiety; -Pre-test cognitive anxiety and basal self-confidence; -Post-test cognitive anxiety and basal somatic anxiety; -Post-test cognitive anxiety and pre-test state anxiety; -Pre-test somatic pre-test anxiety and pre-test cognitive anxiety; -Pre-test somatic anxiety and pre-test self-confidence; -Post-test somatic anxiety and pre-test somatic anxiety; -Post-test somatic anxiety and post-test cognitive anxiety; -Post-test somatic anxiety and post-test self-confidence; -Post-test somatic anxiety and post-test cognitive anxiety; -Post-test somatic anxiety and post-test self-confidence. Post-test self-confidence and pre-test cognitive anxiety; - Post-test self-confidence and post-test cognitive anxiety.

DISCUSSION

The objective of the present study was to analyse the relationships between completing a specific driving test and the levels of anxiety and self-confidence obtained in a sample composed of students from the Traffic School of the Guardia Civil. Data were recorded during a Rest situation (baseline), prior to the test (Pre-test), and after the test (Post-test). The results showed that cognitive anxiety, somatic anxiety, and state anxiety were higher before the driving test than after it. On the other hand, both somatic anxiety and state anxiety were higher before the start of the test than in the baseline situation. Regarding self-confidence, no significant differences were found to support the hypothesis, although there are studies that might explain this. Finally, higher levels of general anxiety were observed after completing the specific driving test compared to the levels recorded in the baseline situation.

The first hypothesis is partially fulfilled. Although the results showed higher levels of cognitive anxiety in the pre-test compared to the post-test, there were no significant differences between the values observed in the pre-test and the post-test, nor their hypothetical relationship with the baseline. It is important to remember that the motorcycle driving test was conducted in an academic context, subject to continuous evaluation. There are studies that have evaluated academic emotions and found that post-evaluative cognitive anxiety could be more intense in students who were uncertain about their performance. These students experienced high levels of uncertainty about the results and concern over future consequences. Rumination and negative self-evaluation increased anxiety levels after completing the evaluative task (Pekrun, Goetz, & Perry, 2002). This would justify the data reflected in the results related to post-test cognitive anxiety.

The second hypothesis is almost entirely confirmed. The results reflect the existence of significant differences between the pre-test and post-test, as well as between the pre-test and the baseline, confirming the trend observed in other studies, such as the one conducted with fighter pilots related to the psychophysiological response during aerial attack situations in simulated flight (Hormeño & Clemente, 2019). In this study, an increase in somatic anxiety was observed in the pilots before the simulated flight compared to afterward. Regarding the relationship between the baseline and post-test, although differences exist, they are not significant. This could be related to the idiosyncrasies of the situation and the timing of the baseline recording, which was carried out when the civil guards were beginning the demanding academic regimen of the Driving Course, potentially interfering with the baseline data.

Although the third hypothesis is not fulfilled, there are studies that offer similar information to the results obtained. Specifically, the one conducted with parachutists from military units, in which the novices, likewise, did not show significant differences related to self-confidence before and after the jump (Clemente et al., 2016). In line with this, and in relation to the analysis of the subjective perception of self-confidence, the study also reflected that the group of veteran parachutists did show higher values than the novices after the jump compared to pre-jump. A possible cause could be related to the level of experience. This is a key factor in enhancing effectiveness and thereby improving performance, emphasizing the importance of training in real-life situations (Bandura, 1990).

The fourth hypothesis was fully supported. The anxiety values show a clear and consistent pattern in which general anxiety levels vary significantly across the different situations: baseline, before the test, and after the test. In the baseline situation, general anxiety levels were relatively low, which is consistent with the perception of being distant from risk, generating relative calm in the absence of an imminent threat or challenge, such as the driving test. However, as expected, before the test, general anxiety levels increased significantly. This increase could be related to the imminent participation in the driving test, which triggered emotional and psychological activation, consistent with an evaluative and potentially stressful situation, as supported by the theory of anticipatory anxiety (Barlow et al., 1996). This theory highlights how individuals experience increased anxiety when anticipating an important challenge.

The fifth hypothesis meets expectations. Thus, the older group showed higher levels of self-confidence before the test, which seems logical, as older individuals are typically associated with more reflective and mature profiles (Jones, Hanton, and Connaughton, 2002). This study, which explored self-confidence in sports performance, not only linked sports practice with increased self-confidence but also observed significant differences in how younger athletes and older adults manage their self-confidence. While younger athletes exhibited more dramatic fluctuations in their self-confidence depending on recent test results, older adults who managed to maintain stable self-confidence tended to perform more consistently. Older adults with higher self-confidence achieved better results, even when facing greater physical challenges than younger athletes. This study emphasizes that, although self-confidence is beneficial at all ages, older adults may gain greater benefits from maintaining high confidence before a test, as they tend to face more significant physical and psychological strain.

Regarding the sixth hypothesis, it is not supported. There were higher levels of self-confidence in the group of individuals with less time holding a driver's license compared to those with longer possession of the license. This could be related to regular practice, as someone who has had a license for a long time but does not drive regularly may develop lower levels of self-confidence than someone who has had the license for a shorter time but drives frequently. The latter group may acquire more skills through regular practice, leading to a natural increase in self-confidence.

In relation to the seventh hypothesis, related to the frequency of daily driving practice, the data do not reflect the expected hypothesis. Interestingly, the group that dedicated more days per week to practice (high frequency practice group), showed higher levels of anxiety than the subjects who practiced driving less days per week (low frequency practice group). In this sense, it is likely to have affected the self-teaching method used by the participants during the practice time, which does not fit with the model called "*deliberate practice*". This model explains how mastery of a skill comes not simply from repetition, but from the way it is practiced. Unlike regular practice, which can be repetitive or unfocused, deliberate practice, compatible with the "*competency-based*" educational model and whose characteristics are situated and contextualized learning in the specific environment and daily activities centred on the subject, proposes that to acquire the level of expertise in a skill, it must be subject, not only to the time spent in the repetition of the practice, but also to the quality, process and specificity of the practice (Ericsson, 2008). For this reason, the absence of specific competencies could have resulted in more interference in those subjects with more practice time but self-taught.

The eighth and final hypothesis, related to the correlation between the variables, is generally fulfilled. The results reflect that, for the most part, there is a significant relationship between the various forms of anxiety and self-confidence at different stages of the study. The resulting correlation generally suggests that as levels of anxiety (state, cognitive, and somatic) increase, self-confidence tends to decrease. This finding is consistent with existing literature, which highlights how anxiety can negatively impact the perception of competence and a person's self-control, especially in evaluative or competitive contexts (Bandura, 1997). Aside from the general correlations, several exceptions were noted where no correlation was obtained. These exceptions include the following:

1. **Baseline state anxiety and pre-test cognitive anxiety**. Baseline state anxiety represents a general level of anxiety at rest, while pre-test cognitive anxiety is more related to specific concerns before

the test. This suggests that resting anxiety does not necessarily predict specific cognitive worries related to performance.

2. **Pre-test state anxiety and post-test cognitive anxiety**. The lack of correlation between these two types of anxiety may indicate that the anxiety experienced before a test does not always influence subsequent cognitive anxiety, which may be more related to the evaluation of one's performance after completing the test.
3. **Pre-test cognitive anxiety and somatic anxiety.** Although both types of anxiety are generally interrelated, the absence of correlation suggests that some individuals may have experienced anxious thoughts without manifesting physical symptoms, potentially depending on the individual profile of certain participants.
4. **Pre-test cognitive anxiety and baseline self-confidence**. The lack of correlation may reflect that pre-test cognitive concerns do not always affect the stable self-confidence that individuals possess before facing a situation. Some people may maintain a strong sense of self-confidence regardless of their cognitive anxiety before the test.
5. **Post-test cognitive anxiety and baseline somatic anxiety**. The absence of correlation indicates that post-test cognitive anxiety is not necessarily related to resting levels of somatic anxiety, suggesting that worries and physical symptoms may operate independently at different times.
6. **Post-test cognitive anxiety and pre-test state anxiety**. This suggests that the emotional state before the test did not affect the cognitive anxiety that may arise after the evaluation, as performance-related worries may depend more on external experiences than on the test itself.
7. **Pre-test somatic anxiety and pre-test cognitive anxiety**. The lack of correlation may indicate that, for some individuals, the physical symptoms of anxiety and cognitive worries may have experienced different levels of activation, implying that not all participants responded in the same way to the evaluative situation.
8. **Pre-test somatic anxiety and pre-test self-confidence**. The lack of correlation may suggest that some individuals may have felt physical symptoms of anxiety without this affecting their perception of self-confidence before a test.
9. **Post-test somatic anxiety and pre-test somatic anxiety**. The absence of this correlation may suggest that somatic symptoms may have changed significantly after the test based on how participants evaluated their performance, regardless of how they felt physically beforehand.
10. **Post-test somatic anxiety and post-test cognitive anxiety**. The lack of correlation suggests that, although both types of anxiety should have been present after the test, they manifested independently, depending on the individual's perception of their performance.
11. **Post-test somatic anxiety and post-test self-confidence**. This lack of correlation suggests that physical symptoms of anxiety after the test did not directly affect the perception of self-confidence, as participants may have felt relieved after completing the task, potentially boosting their self-confidence.
12. **Post-test self-confidence and pre-test cognitive anxiety**. The lack of correlation between these two variables suggests that the concerns expressed before the start of the test did not necessarily affect self-confidence afterward, as participants may have reevaluated their performance after completing the test.
13. **Post-test self-confidence and post-test cognitive anxiety**. This absence of correlation may indicate that post-test cognitive anxiety did not affect subsequent self-confidence, which may also reflect those participants felt satisfied with their results despite their worries.

Finally, after the test, general anxiety levels decreased significantly, although they did not return to baseline levels. This decrease reflects the reduction of uncertainty and relief after completing the test. However, the fact that anxiety levels did not fully return to initial values may be related to the self-perception of performance and post-test evaluation, factors that tend to maintain a certain level of emotional activation even after overcoming a stressful situation.

CONCLUSIONS

The results obtained reveal that the levels of state anxiety, cognitive anxiety, and somatic anxiety were significantly higher before the driving test than after it. Both somatic anxiety and state anxiety were greater before the test than in the baseline condition. State anxiety showed higher values after the test compared to those obtained in the baseline measurement. Additionally, it showed higher values before the test in participants who had practiced self-taught for four or more days a week compared to those who had practiced between one and three days. Self-confidence showed significant differences both in relation to the established age groups, with those aged ≥40 years displaying higher values than those aged 30 to 39, and in the groups related to the length of time holding a driver's license, with higher values observed in the group with less than 60 months of possession compared to those with more than 60 months. The observed correlations mainly support how anxiety negatively impacts self-confidence. The exceptions highlight the importance of considering the context and individual emotional state. The variables of anxiety and self-confidence may be influenced by various factors. The lack of correlation in some cases indicates that these dynamics are not always linear or predictable. This finding emphasizes the need for a more nuanced approach in correlation studies between anxiety and self-confidence that takes into account individual differences and the specificities of each situation.

In summary, the results of this study highlight the complexity of the interactions between anxiety and self-confidence in evaluative contexts, suggesting areas for improvement in both the training of the Civil Guard officers and future research on psychological management in driving tests. It is crucial to consider the development of intervention programs that strengthen participants' self-confidence by incorporating strategies that promote a positive mental state and reduce anxiety.

AUTHOR CONTRIBUTIONS

Miguel Ángel Moyano-Galán was involved in data curation, selection of volunteers, methodology, investigation, resources, writing-review & editing, supervision, and final approval the manuscript. Juan Pedro Fuentes-Garcia involved in conceptualization, methodology, resources, selection of volunteers, validation, procedure administration, formal analysis, data curation and collection, writing-original draft, and final approval the manuscript. Santos Villafaina was involved in conceptualization, methodology, formal analysis, supervision, writing-original draft, approved the final version.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Morpho-functional characterization of an elite Chilean mountain runner: Insights from a high-performance case study

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ABSTRACT

Trail running (TR) is an endurance sport practised on irregular natural terrain with significant elevation changes. The aim was to analyse cardiorespiratory fitness parameters, bilateral body composition and maximal strength profiles in the lower limbs of elite Chilean trail runners. A 26-year-old Chilean amateur ultra trail runner was studied (body weight: 62.3 kg, height: 1.71 m, BMI: 21.2 kg/m², lean mass: 54 kg (86.6%), muscle mass: 30.3 kg (48.6%), fat mass: 8.3 kg (13.3%) and a skeletal muscle mass index of 7.5 kg/m²). The subject participated in three laboratory sessions: 1) anthropometric and pulmonary measurements, 2) cardiopulmonary exercise testing (CPET) with heart rate variability (HRV) assessment, and 3) isometric and isokinetic lower limb strength assessment. During the CPET, VO_{2max}, ventilatory and HRV thresholds were measured using the DFA a1 algorithm. Quadriceps muscle oxygen saturation (SmO_2) was also recorded. The runner presented a VO_{2max} of 75 ml/kg/min. SmO_2 values during CPET were 67.2% at rest, 38.5% at VT_1, 26.8% at VT_2 and 17.2% at VO_{2max}. The results showed that the first heart rate variability threshold ($HRVT_1$) coincided with the ventilatory thresholds (VT_1 and VT_2). Isometric and isokinetic evaluation revealed a higher eccentric flexion/concentric extension ratio in the right hip compared to the left, with values of 2.58 for the right and 2.25 for the left. Aerobic fitness is essential for trail running performance. Ventilatory thresholds and HRV, together with SmO_2, may be useful tools for monitoring muscle fatigue. The observed muscle strength imbalances between limbs highlight the importance of training for strength symmetry to maximise performance and reduce the risk of injury. Future studies on muscle oxygenation, respiratory function and muscle asymmetries may improve training strategies in TR.

Keywords: Performance analysis, Endurance performance, Off-road running, Mountain running, Elevation gain, Physiology, Cardiorespiratory.

Cite this article as:
Nieto-Jiménez, C., Baez-San Martin, E., Rojas-Valverde, D., Yáñez-Sepúlveda, R., & Tuesta, M. (2025). Morpho-functional characterization of an elite Chilean mountain runner: Insights from a high-performance case study. *Journal of Human Sport and Exercise, 20*(2), 409-418. https://doi.org/10.55860/7xs51s84

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Submitted for publication September 28, 2024.
Accepted for publication December 11, 2024.
Published January 03, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/7xs51s84

INTRODUCTION

Trail running (TR) is an endurance sport performed on irregular natural terrain, often characterised by significant variations in altitude (Giovanelli, Ortiz, Henninger, & Kram, 2016). The unique demands of TR, such as uneven surfaces and steep slopes, place substantial physiological stress on the musculoskeletal system (e.g., eccentric impact), as well as on the cardiorespiratory and aerobic energy systems (e.g., sudden shifts in energy requirements), exceeding those typically encountered in road races like marathons (Vernillo et al., 2017). Training in natural environments elevates the metabolic cost of running, thereby fostering greater development of aerobic capacity (Millet, Martin, Lattier, & Ballay, 2011; Scheer, Vieluf, Janssen, & Heitkamp, 2019). In this context, higher levels of maximal oxygen uptake (VO_{2max}) (Balducci, Clémençon, Trama, Blache, & Hautier, 2017; Ehrström, Tartaruga, Easthope, Brisswalter, Morin, & Vercruyssen, 2018) and improved intensity at metabolic thresholds have been linked to better performance in TR athletes (Scheer et al., 2019; Vernillo et al., 2017).

Recent studies highlight the utility of heart rate variability (HRV), derived from nonlinear analyses of electrocardiogram RR intervals, for detecting key metabolic thresholds (both aerobic and anaerobic) (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996). Among the various methods, the alpha-1 detrended fluctuation analysis (DFA a1) algorithm has gained traction due to its reliability in identifying these thresholds (Schaffarczyk et al., 2023).

Compared to road runners, TR training has been shown to significantly enhance lower limb strength (Balducci et al., 2017). This strength gain is attributed to the demands of uphill running, which involves greater concentric muscle activity, and downhill running, which requires heightened eccentric muscle activity, both of which are integral to TR races (Sabater-Pastor, Tomazin, Millet, Verney, Féasson, & Millet, 2023; Drum, Rappelt, Held, & Donath, 2023). Although hip strength adaptations are expected as well, this aspect remains under-documented. Furthermore, not only is maximal strength in key muscle groups crucial for performance, particularly in lower limbs, but so too is balance between agonist and antagonist muscle forces, as well as bilateral symmetry across body segments (Schache, Blanch, Rath, Wrigley, & Bennell, 2001). Muscle imbalances could have a detrimental impact on TR performance (Gabbett, 2016) and maintaining symmetrical muscle mass distribution is essential for minimising the risk of musculoskeletal injury (Zifchock, Davis, & Hamill, 2006).

This study aimed to analyse the cardiorespiratory fitness parameters during a cardiopulmonary exercise test (CPET), bilateral body composition, and maximal strength profiles of the lower limbs in an elite Chilean trail runner. This holistic approach provides valuable insights into the physiological and biomechanical demands placed on elite trail runners, highlighting critical factors such as oxygen uptake, muscle imbalances, and strength asymmetries that could impact performance and injury risk.

By focusing on an elite Chilean trail runner, this case study aims to contribute to understanding how specific physical and metabolic adaptations in high-performance athletes can be optimised for enhanced endurance and performance in trail running. This case-kind type of approach is common in the literature and valuable to understand how high-level ultra runners perform, considering its unique characteristics and a limited number of athletes (Millet, & Jornet, 2019; Garcia de Dionisio, Gómez-Carmona, Bastida-Castillo, Rojas-Valverde, & Pino-Ortega; 2020).

METHODOLOGY

Participant

This study was conducted on a high-performance Chilean male amateur ultra-trail runner with a Ultra Trail Mont-Blanc® (UTMB) index of 828 (highest UTMB index 935) who competes in the categories ultra-trail short (<43 km) and medium (43-69 km) and qualified for UTMB World Series Finals. This level allows him to be considered the best in his category in Chile in 2024. The runner was asked to visit the laboratory three times for morpho functional measurements in May 2024. For the evaluation date, the age of the athlete was 26 years, body weight 62.3 kg, height 1.71m, BMI 21.2 kg/m², lean mass 54 kg (86.6%), muscle mass 30.3 kg (48.6%), fat mass 8.3 kg (13.3%) and a skeletal mass index of 7.5 kg/m² (Table 1). According to his sports planning, the subject has complied with a volume of 15 ± 3 hours of physical training distributed in 15.6% of general physical preparation (place exercises), 35.4% of cycling, 25% of running and 24% of TR runs (characteristics).

The variables of training reported were volume (403 h/year), distance (4107 km/year), distance climbed (58795 m/year), and internal training load according to the TRIMP score (Foster et al., 2001). The procedures that were carried out to obtain the study variables were made known to the athlete before starting the measurements and after signing a written informed consent. All procedures were approved by the Scientific Ethics Committee of the Universidad Viña del Mar (Code R62-19a) and were carried out following the ethical recommendations described in the Declaration of Helsinki.

Table 1. General and anthropometric characteristics.

Parameters	Value
Age (y)	26
Sex	male
Weight (kg)	62.30
Height (m)	1.71
Muscle mass (kg)	30.30
Fat mass (kg)	8.30 (13.30%)
BMI (kg/m^2)	21.30
Lean body mass (kg)	54.00
Skeletal mass index (kg/m^2)	7.50

Procedures

The assessment was performed in the laboratory of the Kinesiology School of the Andres Bello University of Viña del Mar, Chile. The three evaluation days were separated by 24 and 48 hours of rest. All measurements were carried out between 10:00 am and 12:00 am. The distribution of these was as follows: day 1: anthropometric and pulmonary measurements (i.e., spirometry, and respiratory pressures), day 2: 24 hours later CPET (i.e., VO_{2max}, heart rate) with determination of heart rate variability (RR time series), and day 3: 48 hours later isometric and isokinetic lower limbs strength assessments were carried out. Before and during the evaluation period, it was recommended to avoid the consumption of any stimulant or diuretic food or liquid (e.g., coffee or tea) in the hours prior to the evaluation sessions.

Cardiopulmonary exercise testing

CPET was performed with a metabolic cart (Metalyzer 3B, CortexMedical, Germany). Before starting the exercise, 1 minute of rest was recorded. Physical exercise was performed on a treadmill (Runrace, Technogym, Italy) in 1-minute stages (S) with changes in speed and gradient as follows: S1: 5.5 km/h and

0%, S2: 7 km/h and 1%, S3: 7 km/h and 5%, S4: 8 km/h and 5%, S5: 8 km/h and 10%, S6: 9 km/h and 10%, S7: 9 km/h and 15% and S8: 10 km/h and 15%. From stage 9 on, the speed was increased by 1 km/h every minute, maintaining a constant slope of 15% until fatigue.

The VO_{2max} and ventilatory thresholds (VT_1 and VT_2) were obtained from the CPET following previous recommendations (Binder et al., 2008). During CPET, RR time series values were also obtained with a chest strap (H10, Polar, Finland), which were recorded with a heart monitor (V800, Polar, Finland) to calculate heart rate variability (HRV) thresholds through the Kubios program (version 3.1.0, University of Eastern Finland, Kuopio, Finland). In addition, the quadriceps muscle's oxygen saturation (SmO_2) was recorded with near-field infrared spectroscopy equipment (Moxy monitor, Fortiori Design LLC, USA) throughout the test.

Heart Rate Variability Thresholds

RR time series during exercise (i.e., CPET) were downloaded from the heart monitor (V800, Polar, Finland) using the Polar Flow program (version 3.0.0.1337, Polar Finland). Subsequently, data collected with a sampling frequency of 1000 Hz were analysed by the Kubios HRV analysis program (version 3.1.0, University of Eastern Finland, Kuopio, Finland). According to previous recommendations, the DFA a1 algorithm was used to determine HRV thresholds with a time window of 120 seconds (Chen et al., 2002). A DFA a1 just below 0.75 and 0.5 was used to obtain $HRVT_1$ and $HRVT_2$ respectively (Rogers et al. 2021).

Spirometry and inspiratory muscle strength

Lung volumes were measured via forced spirometry with a metabolic cart (Metalyzer 3B, CortexMedical, Germany). Respiratory muscle strength was estimated from the measurement of peak inspiratory/expiratory pressures (PI_{max} [cmH_2O]/PE_{max} [cmH_2O]) with an electronic manovacuometer (MicroRPM, Carefusion, USA). The protocols recommended by the American Thoracic Society and the European Respiratory Society (ATS/ERS 2002) were used for both measurements. Prior to the spirometry measurements, the equipment was calibrated with a 3-liter syringe. Then, FEV_1 (L), FVC (L), and FEV_1/FVC (%) were recorded. Familiarisation of the use of the devices was performed for both evaluations.

For respiratory pressures (strength) only, a warm-up was performed at 40% of the highest inspiratory and expiratory pressure during familiarization (Volianitis, McConnell, & Jones, 2001). The warm-up consisted of two sets of 15 repetitions with a one-minute rest between each set. Both times, respiratory pressures were measured with the subject seated (with a chair fixed to the floor), with the soles of the feet resting on the floor (shoulder-width apart), and with a nose clip.

Isokinetic strength evaluation of the lower limbs

Concentric (Con) and eccentric (Ecc) isokinetic strength of the hip and knee muscles was assessed with a functional electromechanical dynamometer (Health, Dynasystem, Simotech). Hip abduction, adduction, extension and flexion, and knee flexion and extension movements were assessed bilaterally at a speed of 0.5 m/s. Hip positions and movements were adjusted according to (Contreras et al., 2023) Concentric (90° to 180° degrees) and eccentric (180° to 90° degrees) extension and concentric (135° to 90° degrees) and eccentric (90° to 135° degrees) flexion of the knee were performed with the participant in a seated position in an open kinetic chain.

In addition, functional bilateral index of the stronger leg relative to the weaker leg were calculated (eccentric agonist/concentric antagonist). For the warm-up, body positioning, range of motion, and execution were standardised prior to the measurements.

RESULTS

Table 2. Cardiorespiratory and autonomic parameters during cardiopulmonary exercise test.

Parameters	Resting	VT_1 ($HRVT_1$)	VT_2 ($HRVT_2$)	Maximum effort
VO_2 (ml/min/kg)	2.0	41 (30.4)	58 (54.4)	74
%VO_{2max}	2.0	60 (58)	77 (71.4)	100
HR (bpm)	51.0	140 (141)	160 (157)	175
%HR_{max}	29.0	80 (81)	91 (90)	100
VE_{max} (L/min)	7.1	49.8 (55.8)	88.4 (87.1)	152
RER	0.75	0.83 (0.84)	1.01 (1.01)	1.16
Speed (km/h)		9 (9)	10 (10)	13
Grade (%)		10 (10)	15 (15)	15
MAS (km/h)				13 (15%-slope)
Quadriceps SmO_2(%)		38.5 (35.7)	26.8 (31.9)	17.2

Note. HR: heart rate; $HRVT_{1-2}$: heart rate variability thresholds one and two; MAS: maximal aerobic speed; RER: respiratory exchange rate; VT_{1-2}: ventilatory thresholds one and two.

Table 3. Muscle respiratory strength and pulmonary function

Assessment	Value (LLN)
Spirometry	
CVF (L)	5.09 (4.06)
VEF1 (L)	4.44 (3.39)
VEF1/CVF (%)	87
Respiratory muscle pressure	
PI_{max} (cmH_2O)	139
PE_{max} (cmH_2O)	171

Note. FVC: forced vital capacity, FEV_1: forced expiratory volume, LLN: Lower limit of normality.

Table 4. Isokinetic (0.5 m/s) and isometric strength peak and power in lower limbs.

Side	Movement	Isokinetic strength (kg)		Functional ratio
		Concentric	Eccentric	Ecc/Conc
Right Hip				
	Flexion	36.41	58.15	2.58
	Extension	22.50	29.69	
	Abductor	18.29	30.27	1.13
	Adductor	26.71	48.92	
Left Hip				
	Flexion	37.75	54.47	2.25
	Extension	24.20	29.20	
	Abductor	11.16	20.57	0.71
	Adductor	28.93	42.60	
Right knee				
	Flexion	44.71	42.31	0.91
	Extension	46.58	72.70	
Left knee				
	Flexion	41.44	71.42	1.61
	Extension	44.24	91.58	

Note. Conc: Concentric muscle action, Ecc: Eccentric muscle action.

Cardiopulmonary exercise test and Heart Rate Variability Thresholds

During the exercise test, the subject reached the maximum physiological effort parameters, reaching 91% of his predicted maximum heart rate and a respiratory exchange rate of 1.17.In addition to the cardiopulmonary and external load responses in energy thresholds obtained by ventilatory (VT_1 and VT_2) and heart rate variability ($HRVT_1$ and $HRVT_2$) methods, the maximum values for internal (cardiorespiratory) and external (i.e., speed) physiological loads are shown in Table 2.

Spirometry and respiratory pressures

Table 3 shows the normal values obtained from spirometry.

Lower limbs strength

Tables 4 shows the isokinetic hip and knee strength values, strength ratios of antagonistic muscle actions and bilateral muscle symmetry of both joints, respectively.

DISCUSSION

A higher aerobic aptitude is a fundamental factor for endurance athletes' performance in sports. In TR, this is no different; previous studies have shown that runners with better sporting performance have higher VO_{2max} values (Pastor, Besson, Varesco, Parent, Fanget, Koral, & Millet, 2022). In our participant, VO_{2max} was obtained with a maximal exercise test with increasing speed and gradient, reaching maximums of 13 km/h and 15%, respectively. Our participant had VO_{2max} of 74 ml/kg/min in the maximal incremental treadmill test (RER: 1.16), which was higher than those observed in the literature for his category (short and moderate distance ultra-trail) (~60-70 ml/kg/min (Fornasiero, Savoldelli, Fruet, Boccia, Pellegrini, & Schena, 2018). The effort (%VO_{2max}) at threshold VT_1 has been recognised as a strong predictor of performance in TR. Our athlete VT_1 was observed at 60% VO_{2max}, within the range observed in the scientific literature (Doucende et al., 2022). The velocity at VT_1 was lower with concerning to other studies 9 km/h vs 13.3 km/h (Scheer et al.,2019) and 11.2 km/h (Martinez-Navarro et al., 2021), which can be explained by a higher slope reached during the test at that point, i.e., (10% vs 1.0% (Scheer et al.,2019) and 0% (Scheer et al.,2019). It is worth noting that higher slope values (~15-25%) achieved in a maximal effort test have been strongly related to trail running performance in the laboratory and field (Doucende et al., 2022).

Along the same lines, the first threshold of heart rate variability ($HRVT_1$) showed similarity with physiological variables related to the first (VT_1) and second ventilatory threshold (VT_2). Previous studies have shown a high reliability of using HRV to detect metabolic system transition thresholds (Kaufmann et al.,2023). The low complexity and cost of HRV could enhance its use in the control of training in trail running, as has occurred in other endurance sports (Lundstrom et al., 2022). Likewise, SmO_2 also had close values with ventilatory thresholds (ΔSmO_2; VT_1-$HRVT_1$: -2.8% and VT_2-$HRVT_2$: +4.9%). This is very relevant since it would allow studying the oxygen delivery/utilization of the main locomotor muscle during the race, showing the muscle metabolic adjustments due to the duration (time of the race) and the slopes of the course (positive or negative). This will allow, among other things, the adjustment of nutritional supplementation during the race. Currently, in the scientific literature, there is no SmO_2 data on trail runners; however, given the convenience of its use and the reliability of the measurements, it will be necessary to guide studies in the analysis of muscle oxygenation in this sport.

From the onset of the maximal exercise test, the participant was proportionally increasing the oxygen demand (SmO_2) of the primary locomotor muscle (i.e., quadriceps) with decreases in saturation of 67.2%, 38.5%, 26.8% and 17.2% for resting, VT_1, VT_2 and VO_{2max}, respectively. These findings are consistent with results obtained in other endurance sports (Vasquez Bonilla et al., 2023). Therefore, further studies evaluating the use of SmO_2 to monitor muscle fatigue thresholds in real time would be beneficial, allowing more accurate adjustments to training loads (Murias et al., 2013).

The pulmonary function study showed that the participant has higher capacities and volumes than predicted for age, sex and height from the Global Lung Function Initiative. A FVC of 5.09 l (predicted FVC: 4.61 l), FEV_1 of 4.44 l (predicted FEV_1: 3.93 l), and an FEV_1/FVC ratio of 87% (predicted FEV_1/FVC: 85.3%) are indicative of lung function within ranges in mountain ultramarathon runners (Martinez-Navarro et al., 2020). Respiratory muscle pressures have shown a high correlation with performance in endurance athletes (Martinez-Navarro et al., 2020). Our athlete showed slightly higher values in inspiratory pressure (139 cmH_2O) and slightly lower values in expiratory pressure (171 cmH_2O) with respect to predicted for his sex and age against a sample of healthy males (PI_{max}: 136.2 ± 25.1 cmH_2O; PE_{max}: 184 ± 39.5 cmH_2O) (Lista-Paze et al. 2023). Higher basal PI_{max} may have a greater beneficial effect on performance, as it was previously shown that a long-duration ultra-trail run significantly decreased PI_{max} in a sample of competitive male trail runners (PI_{max} pre-run: 115.74 ± 20.92 cmH_2O; PI_{max} post-run: 92.0 ± 20.0 cmH_2O; Δ-26.1%) (Martinez-Navarro et al., 2021). It should be noted that the participant in our study had not specifically trained the respiratory musculature before.

In trail runners, concentric gluteal and quadriceps strength for hip and knee extension, respectively, will be required during ascents on positive slopes and eccentric strength during descents with negative slopes. In the evaluated athlete, we observed that the concentric isokinetic force during hip extension was similar (left: 24.20 kg vs right 22.50 kg). However, the isokinetic concentric extension at the knee was slightly greater on the right (46.58 kg) than on the left (44.24 kg).. The results of the eccentric extension of the hip were similar (right hip: 29.69 kg vs left hip: 29.20 kg). However, for the knee, the difference was significantly greater for left than right strength (91.58 kg vs 72.70 kg, respectively). Another relevant aspect was that the relationship between the abductor and adductor components of the hip, which give stability to this joint during flexion and extension movements, showed significant differences between concentric and eccentric abduction strength in favour of the right hip (Conc: 18.29 vs 11.16 kg; Ecc: 30.27 vs 20.57 kg). Now, it is recognized that prolonged exercise causes a decrease in lower limbs strength (Millet et al., 1985). Decreased knee flexor and extensor torque and functional eccentric/concentric ratios have been observed following fatiguing physical exertion (Oliveira et al., 2008). In our participant, a higher functional eccentric flexion/concentric extension ratio was observed in the right versus left hip (2.58 vs 2.25). However, the eccentric flexion to concentric extension ratio at the knee was higher on the left than on the right (1.61 vs 0.91). For the ratios of eccentric hip abduction and concentric hip adduction, higher values were observed in the right versus the left hip (1.13 vs. 0.71). The strength analysis presented in this article reveals decompensations between muscle groups, even though this sport has balanced bilateral demands. Improving the symmetry of stabilizing and locomotor forces will ensure optimal performance and reduce the risk of injury.

Limitations

This study presents some limitations that should be addressed. First, it focuses on a single high-performance Chilean trail runner, limiting the generalizability of the findings to other athletes or populations. The results may not apply to runners with different experience levels, ages, or competitive environments. Additionally, the environmental conditions typical of trail running, such as altitude and terrain, were not replicated in the lab, potentially affecting the external validity of the results but conserving the results transference. Lastly, important physiological markers such as lactate concentration and neuromuscular fatigue indicators were not measured, which could provide a more comprehensive understanding of endurance performance and fatigue in trail running.

CONCLUSION

In conclusion, high aerobic fitness remains key to excellent performance in trail running. Ventilatory thresholds and heart rate variability align with previous studies, and muscle oxygen saturation showed, in this case, a close relationship to these thresholds, suggesting its potential usefulness for real-time muscle fatigue monitoring. The participant's lung function is within optimal ranges, although differences in locomotor muscle strength between the two sides of the body indicate the need for improved muscle symmetry. To maximise performance and reduce the risk of injury, it is crucial to focus training on force symmetry and consider using SmO_2 as a monitoring tool. These results suggest that future studies on muscle oxygenation, respiratory function and muscle strength symmetries may offer new insights to improve training strategies in trail running.

Practical applications

The findings of this case study provide practical insights for athletes and coaches in trail running. Monitoring ventilatory thresholds and HRV can help assess aerobic and anaerobic capacity, aiding in more targeted training interventions. HRV is a cost-effective, non-invasive tool for evaluating endurance performance and recovery. The study also emphasizes the importance of bilateral muscle symmetry, as strength imbalances between limbs can increase injury risk and reduce performance, especially on challenging terrain. Specific strength training programs are recommended to correct these asymmetries, particularly in the hip and knee. Additionally, muscle oxygen saturation monitoring offers real-time feedback on muscle fatigue, enabling athletes to adjust pacing and nutrition strategies. Incorporating these tools into regular training and competition monitoring could optimize trail running performance.

AUTHOR CONTRIBUTIONS

Study concept and design, drafting the article: Marcelo Tuesta and Claudio Nieto-Jimenez. Its critical revision: Marcelo Tuesta, Claudio Nieto-Jimenez and Rodrigo Yañez-Sepulveda. Data collection: Marcelo Tuesta and Claudio Nieto-Jimenez. Analysis: Marcelo Tuesta, Claudio Nieto-Jimenez and Daniel Rojas-Valverde. Final approval of the version to be published: Marcelo Tuesta, Claudio Nieto-Jimenez, Rodrigo Yañez-Sepulveda, Eduardo Baez-San Martin and Daniel Rojas-Valverde.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Caloric restriction improves perceived exertion while conserving immunity, fatigue, inflammation, and physical performance in male professional soccer players: A controlled randomized trial

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ABSTRACT

Purpose: In athletes, caloric restriction (CR) improves physiological mechanisms, although its effects on professional soccer players are unclear. This study aims to evaluate the effects of CR on physical performance, fatigue, and inflammation in male professional soccer players compared with a no-restriction diet. Methods: This was a controlled, randomized, parallel-group study with 28 participants. The experimental group received a CR diet (−25% of recommended energy intake; mean caloric intake: 2650 kcal/d). Controls received a normal caloric (NC) diet (mean caloric intake: 3500 kcal/d). Both groups received a protein supplement. Six weeks of intervention were followed by 6 weeks without intervention. Thereafter, the participants were allowed to eat ad libitum. The study evaluated leukocytes, lymphocytes, creatine phosphokinase (CPK), urea, testosterone, lactate dehydrogenase (LDH), rate of perceived exertion (RPE), countermovement-jump (CMJ), and squat jump (SJ). Results: Average age was 27.6 ± 4.4 years. After 6 and 12 weeks, differences between the two groups were insignificant in terms of the immune response, fatigue (CPK, urea, testosterone, and cortisol), and inflammation (LDH) (p > .05). The CR group had lower RPE levels at 12 weeks (0.01 vs. 0.62 points; p = .001) than the NC group. Conclusion: CR is an effective intervention for male professional soccer players, because it decreased RPE while preserving biochemical parameters.
Keywords: Sport medicine, Immune response, Biochemical parameters, High performance, Elite sport, Caloric restriction, Fatigue.

Cite this article as:
Garcia-Morales, G. I., Diaz, G., Niño, A., del Campo, J., & Tejero-González, C. (2025). Caloric restriction improves perceived exertion while conserving immunity, fatigue, inflammation, and physical performance in male professional soccer players: A controlled randomized trial. *Journal of Human Sport and Exercise, 20*(2), 419-434. https://doi.org/10.55860/3a6khe67

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Submitted for publication October 25, 2024.
Accepted for publication December 08, 2024.
Published January 03, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/3a6khe67

INTRODUCTION

Soccer is characterized by a diversity of movements and muscle contractions. These factors comprise physiological mechanisms to enhance exercise adaptation and recovery after workouts and optimize physical performance. Compared to other disciplines, soccer generates a significant impact on the biomarkers of muscle damage, inflammation, and fatigue. These factors are directly related to physical performance (Berriel et al., 2020; Khaitin et al., 2021; Silva et al., 2018; Souglis et al., 2015). Athletes aim to enhance their performance and optimize their movement efficiency (Pons et al., 2018). Caloric restriction (CR) is highly effective in accomplishing these objectives. CR restricted dietary energy intake while maintaining nutrient supply to achieve optimal nutrition and avoid malnutrition (Most & Redman, 2020; Rhoads & Anderson, 2022). CR extended lifespan and minimized disease risk (Golbidi et al., 2017). Combined with physical exercise, CR enhance the inflammatory response (Calbet et al., 2017; Hector & Phillips, 2018; Liu et al., 2021).

CR triggered biochemical processes, such as stress pathways, autophagy, reduction of advanced glycation end-products, and hormonal changes, to positively impact physical exercise (Golbidi et al., 2017; Green et al., 2022; Madeo et al., 2019). Mild and moderate CR decreased glucose supply and increased fatty acid oxidation, which are required to provide the ATP demand (Lee & Dixit, 2020; Most & Redman, 2020). These mechanisms are akin to those that occur during exercise (McGee & Hargreaves, 2020; Murphy et al., 2020; Travers et al., 2022) and induce metabolic adaptation with direct benefits for athletes, for example, increased mitochondrial energy efficiency, decreased oxidative damage to tissues, reduced leptin levels, reduced insulin resistance, and decreased energy expenditure during physical activity as a result of increased movement economy (Aragon et al., 2017; Most & Redman, 2020; J. Peos et al., 2019; Pons et al., 2018).

The benefits of CR on the immune response and physical performance have been scarcely investigated in athletes (Zouhal et al., 2020). A squash player who followed a 6-week structured resistance training regimen and moderate energy-restricted diet (70%–78% of estimated energy requirement) showed increased physical performance (Rosimus, 2018). In 12 male athletes who followed a CR of 30%–40% over 6 weeks had decreased blood lactate and decreased heart rate and maintained running rate (Pons et al., 2018). To our knowledge, only two studies have evaluated the effect of CR in professional soccer players (Hammouda et al., 2013). In one trial, 15 male professional soccer players who fasted for 4 weeks with a CR of ~20%. At the end of the intervention, the soccer players showed improved physical performance and decreased heart rate (Hammouda et al., 2013). The second study found similar results in a group of female soccer players (García-Morales et al., 2019).

A combination of exercise and CR could enhance performance and mitigate the inflammatory response in soccer players. However, evidence supporting the effectiveness of CR is scarce and caution is advised before endorsing it as standard practice for soccer players. To address this, a randomized trial was conducted to evaluate the effect of −25% of CR on physical performance, fatigue, and inflammatory response in a sample of male professional soccer players.

MATERIALS AND METHODS

Study design

A randomized, controlled, parallel-group, 1:1 assignment trial was conducted. The experimental group received a calorie-restricted diet (CR group), whereas the control group received a normal caloric diet (NC group). During the study, all players were encouraged to maintain their regular training program (8 h of training/week) without any changes across the competitive season. The measurements were taken at baseline, at 6 weeks, and at the following 6 weeks without dietary interventions and *ad libitum* dietary intake. Primary outcomes included changes in biochemical parameters, physical performance, and perceived effort. This report follows the recommendations of the Proper Reporting of Evidence in Sport and Exercise Nutrition Trials -PRESENT- statement (Betts et al., 2020).

Ethics disclosure

The study followed ethical research practices and received approval from the research ethics committee at the [Anonymous institution for peer review] (CEI 100-1873) on June 21, 2019. The study adhered to the guidelines set forth in the Declaration of Helsinki for the use of human participants in research. All participants read and signed the informed consent document.

Participants

The sample size was estimated for the difference of independent means at the end of the intervention, considering a Confidence Interval of 95%, Power of 80%, Sample Size Ratio 1 and difference of 2 kg. The calculated total sample size was 20 subjects. The players were randomly assigned to the CR and NC groups, with equal distribution of players across various game positions, including goalkeeper, central defence, wing defence, midfielders, forwards, and outside midfielders. The players were not informed about the group they would be assigned to during assignment. During the study, four players withdrew from participation: two due to injuries and two due to team changes (Figure 1).

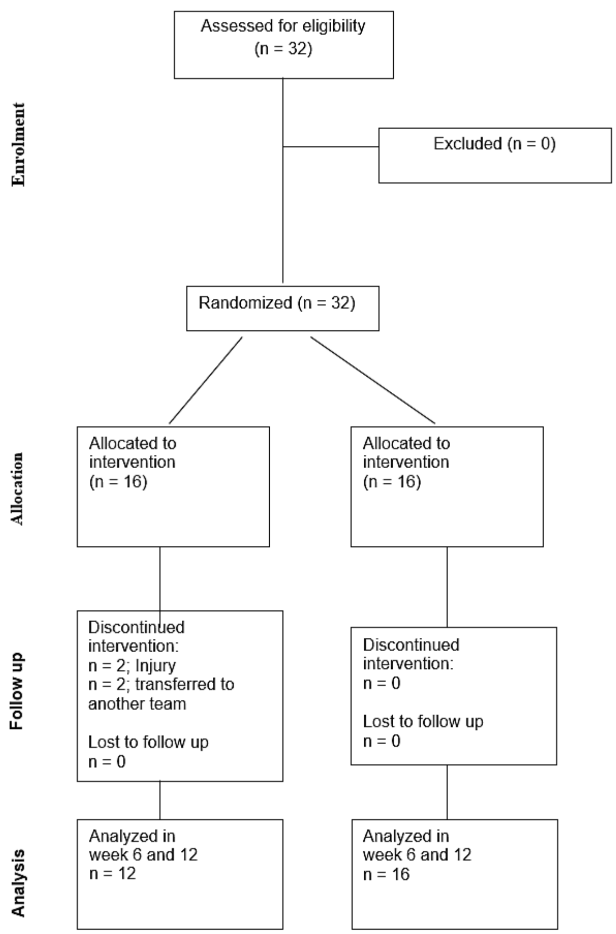

Figure 1. Flow of participants through each stage of the trial.

A total of 32 male professional soccer players from a professional division team soccer participated in this study. Exclusion criteria included players 1) with metabolic diseases, such as cardiovascular, respiratory, gastrointestinal, and thyroid-related; 2) with weight change of ±2 kg in the last month; 3) following special diets (e.g., vegetarian), 4) consuming nutritional supplements in the last month; 5) using medications to control lipids or blood glucose; 6) not complying with all the measurements (physical, physiological, nutritional, and laboratory evaluations), and 7) missing >5% of the scheduled training sessions.

Dietary intervention

Recommended energy intake (REI) was estimated by calculating resting metabolic rate using the Cunningham formula, multiplied by a factor of daily physical activity (rest days) of 1.25, and adding energy expenditure per training/competition days (5 METS -Metabolic Equivalent of Task- for training and 9 METS for competition) (Tinsley et al., 2019). Average REI was 3500 kcal/d for the NC group and 2650 kcal/d for the CR group (reaching a restriction of −25%) (Jagim et al., 2018; Thomas et al., 2016). In order to safeguard the athlete's body composition and performance, this restriction has been implemented (Aragon et al., 2017).

All players were provided with a specific dietary plan, comprising a high-protein, normal-fat, and carbohydrate adjusted diet. The diet was designed to be low in saturated fat and free of trans fats. The players were encouraged to consume polyunsaturated and monounsaturated fats. Carbohydrate intake was adjusted to meet the requirements of each player. The diet excluded added simple sugars. In both groups, macronutrient distribution was 18%–22% protein (1.9–2 g/kg), 22% fat (1 g/kg), and 56%–60% carbohydrate (5–7 g/kg) (Collins et al., 2021; Keen, 2018). During the study, every participant was given a whey protein supplement daily. This supplement was carbohydrate- and fat-free isolate. The participants were instructed to consume 25 g of protein after their morning workout and 12.5 g in the evening (Collins et al., 2021; Keen, 2018).

All players followed a food plan that was calculated and prescribed for them while they were at the training camp and at home. To monitor their diet, a standard menu and diet referrals were prescribed, which were based on energy and nutrient calculations for each group. To assess adherence to the prescribed diet, a dietary assessment was conducted.

Dietary assessment and adherence

Dietary assessment was conducted at the beginning and at 6 and 12 weeks of follow-up. The dietary interview was conducted by a trained nutritionist. Two methods were used to assess dietary intake: 24-h recall and food frequency questionnaire (Bailey, 2021; Salvador Castell, 2015). Artificial food models, measuring cups, and spoons were used to measure food consumed. Mealtimes were directly observed before the interview to ensure accurate information was given. The two methods considered the food types typically eaten; frequency of consumption (daily, weekly, biweekly, or monthly); time of consumption; amount consumed; food preparation method; possible substitutes used; and special characteristics, such as reduced calorie content, low-fat options, vitamin-fortified choices, or high fibre content. Local food composition tables were used for dietary analysis.

Biochemical parameters

During the initial stage of the study, a range of nutritional blood biomarkers were measured to evaluate nutritional status. These included haemoglobin, haematocrit, leukocytes, lymphocytes, ferritin, total protein, albumin, and globulin. Markers of fatigue (creatine phosphokinase [CPK], urea, and total testosterone) and inflammatory response (cortisol and lactate dehydrogenase [LDH]) were assessed at the baseline and follow-up stages. All blood samples were collected in the morning after an 8-h fast with no prior exercise. The samples were processed on the day of collection at a reliable clinical laboratory.

Physical test

The length of vertical jump capacity was used to estimate physical performance, incorporating jump without impulse (squat jump [SJ]) and countermovement-jump (CMJ) tests. Jumps used the "*AXON JUMP*" platform. These tests were performed in the morning, with a prior sleep period of at least 7 h, usual breakfast consumption, room temperature of 24–26 ºC, and humidity between 70%–72%. The tests were performed by a specialized sports doctor and the medical staff of the soccer team.

Perceived exertion test

The evaluation of psychological perception of effort was quantified using the Borg test (rate of perceived exertion [RPE], scale 1–10). The test was administered by a specialized sports doctor and researchers and performed during the first week of training, at baseline, and at follow-up stages, on three alternate days, and after the morning training session. Values were means of the measures in 1 week.

Statistical analysis

Categorical variables were described by frequencies and percentages. Quantitative variables were described by mean and standard deviation. Normal Gaussian distribution of data was verified by the Shapiro–Wilk test. An independent samples *t*-test, the *U* Mann–Whitney test, or χ^2 test, were used to examine differences between groups (CR and NC).

Changes within each group were assessed by comparing follow-up measurements at 6 and 12 weeks. To account for multiple comparisons, Bonferroni's adjustments were applied and all differences were considered statistically significant at $p < .002$. Stata V.14 was used for statistical analysis.

RESULTS

The study enrolled 28 male professional soccer players (average age: 27.6 ± 4.4 years). At baseline, the CR and NC groups showed similar values of nutritional status biomarkers (Table 1).

Table 1. Baseline description of 28 male professional soccer players.

Variable	**Caloric restriction Group**	**Normal diet Group**	***p*-value**
	n = 12	n = 16	
Age, years ◊	27.8 (4.4)	27.5 (4.6)	.86
Position: ƒ			
Goalkeeper	1 (8.3)	1 (6.3)	
Centre back	2 (16.7)	2 (12.5)	
Wing back	2 (16.7)	2 (12.5)	
Centre	4 (33.3)	5 (31.3)	
Winger	3 (25.0)	6 (37.5)	
Nutritional biomarkers ƒ			
Haemoglobin (g/dL)	15.0 (0.8)	14.9 (0.9)	.949
Haematocrit (%)	45.3 (2.6)	46.1 (2.7)	.443
Ferritin (ng/mL)	163.5 (69.4)	158.1 (58)	.837
Total proteins (g/dL)	7.0 (0.4)	7.1 (0.6)	.454
Albumin (g/dL)	4.2 (0.3)	4.3 (0.4)	.413
Globulins (g/dL)	2.7 (0.5)	2.8 (0.4)	.879

Note. ◊ *Values are presented as mean ± SD (standard deviation).* ƒ *Values are presented as frequency and percentage respect to the intervention.*

During the first 6 weeks, the CR group followed the interventions with great adherence ($p < .001$), which were maintained during the 12-week study ($p < .001$). The NC group displayed a significant increase in kcal, protein, and carbohydrate intake during the 12-week study ($p < .001$) (Table 2).

Table 2. Nutritional intake and intervention adherence at baseline and 6 and 12 weeks of follow-up.

Variable	Caloric restriction Group	Normal diet Group	*p*-value
	n = 12	n = 16	
Calorie intake (kcal/kg/d)			
Baseline	41.0 (4.0)	41.5 (4.0)	.6258
6 weeks	30.3 (3.7)	46.9 (4.0)	**.0001**
12 weeks	33.4 (4.4)	45.6 (4.3)	**.0001**
Protein intake (g/kg/d)			
Baseline	2.1 (0.3)	2.1 (0.3)	.9254
6 weeks	2.1 (0.3)	2.5 (0.2)	**.0012**
12 weeks	2.3 (0.3)	2.6 (0.2)	**.0001**
Fat intake (g/kg/d)			
Baseline	1.0 (0.1)	1.0 (0.1)	.885
6 weeks	0.8 (0.2)	1.1 (0.1)	**.0003**
12 weeks	1.0 (0.2)	1.1 (0.1)	.0621
Carbohydrate intake (g/kg/d)			
Baseline	6.1 (0.7)	6.0 (0.7)	.608
6 weeks	3.5 (0.5)	6.7 (0.7)	**.0001**
12 weeks	4.0 (0.5)	6.4 (0.8)	**.0001**

Note. Values are presented as mean ± SD (standard deviation). p values in bold are statistically significant at p < .002.

Table 3. The immune response and changes in fatigue in 28 male professional soccer players at baseline and 6 and 12 weeks of follow-up.

Variables	Caloric restriction Group	Normal diet Group	*p*-value
	n = 12	n = 16	
Immune response			
Leukocytes, # Cells			
Baseline	5298 (1280)	5513 (1316)	.412
Change 6 weeks	579 (2380)	−0.6 (1907)	.48
Change 12 weeks	−8 (2024)	385 (2137)	.681
Lymphocytes, # Cells			
Baseline	2391 (449)	2451 (570)	.774
Change 6 weeks	−94 (662)	−339 (650)	.35
Change 12 weeks	443 (513)	198 (573)	.273
Fatigue			
Creatine kinase, U/L:			
Baseline	290.3 (110.0)	365.6 (263.5)	.926
Change 6 weeks	−45.2 (143.1)	−44.3 (225.3)	.39
Change 12 weeks	56.1 (206.6)	25.4 (250)	.732
Creatine kinase, U/L/kg:			
Baseline	3.8 (1.4)	4.9 (3.4)	.71
Change 6 weeks	−0.59 (1.8)	−0.61 (2.84)	.403
Change 12 weeks	0.72 (2.74)	0.44 (3.37)	.815
Urea, mg/dL:			
Baseline	40.6 (6.9)	38.6 (9.1)	.559
Change 6 weeks	−5.9 (4.7)	−6.3 (7.2)	.849
Change 12 weeks	−1.8 (13.5)	0.5 (6.3)	.591
Testosterone, pg/mL:			
Baseline	6.5 (2.2)	6.8 (1.9)	.458
Change 6 weeks	−1.61 (2.08)	−1.33 (1.58)	.687
Change 12 weeks	2.0 (0.94)	1.18 (1.91)	.202
Cortisol, µg/dL:			
Baseline	12.8 (3.5)	12.9 (2.0)	.902
Change 6 weeks	3.4 (5.0)	4.6 (4.8)	.626
Change 12 weeks	0.3 (6.4)	0.5 (4.4)	.925

Note. Values are presented as mean ± SD (standard deviation). p values in bold are statistically significant at p < .002.

Immune response

The CR group did not experience significant changes ($p > .5$) in leukocyte and lymphocyte counts at the 6- and 12-week marks. The NC group displayed similar immune blood marker results ($p > .5$). These parameters had comparable values between both groups ($p > .5$) (Table 3).

Fatigue and inflammatory response

After 6 weeks, the CR and NC groups showed a decrease in CPK, urea, and testosterone ($p < .05$). After 12 weeks, only CPK and testosterone returned to baseline values ($p > .05$), whereas urea continued to decrease ($p < .05$). Fatigue biomarkers showed no significant differences between both groups ($p > 0.1$) and remained consistent during the study (Table 3). Both groups showed similar alterations in LDH values ($p > .4$), increasing at 6 weeks and decreasing at 12 weeks ($p = .443$).

Physical performance

CR and NC groups exhibited similar changes in SJ and CMJ performance. RPE decreased at 6 weeks but maintained low results only in the CR group ($p = .001$) (Table 4).

Table 4. The changes in physical performance and exertion in 28 male professional soccer players at baseline and 6 and 12 weeks of follow-up.

	Caloric restriction Group	**Normal diet Group**	***p*-value**
	n = 12	**n = 16**	
SJ, cm			
Baseline	38.4 (4.4)	37.0 (3.1)	.327
Change 6 weeks	1.4 (2.2)	1.9 (2.9)	.485
Change 12 weeks	0.3 (2.7)	−0.5 (2.5)	.296
CMJ, cm			
Baseline	41.5 (4.6)	41.4 (4.1)	.946
Change 6 weeks	1.9 (1.5)	1.3 (3.4)	.574
Change 12 weeks	−0.8 (1.5)	0.9 (2.5)	.072
PEr, points			
Baseline	7.9 (0.6)	7.2 (0.6)	.006
Change 6 weeks	−0.51 (0.45)	−0.52 (0.75)	.962
Change 12 weeks	0.01 (0.43)	0.62 (0.41)	**.001**

Note. Values are presented as mean ± SD (standard deviation). p values in bold are statistically significant at p < 0.002. SJ: Squat jump; CMJ: Countermovement jump; PEr: Perceived exertion rating.

DISCUSSION

Because athletes strive to improve performance, incorporating dietary interventions can be highly beneficial. We found that implementing CR can have a positive impact on professional soccer players. Our findings suggest that CR reduced perceived exertion and maintained normal immunity, fatigue, and inflammation.

Immunity and inflammatory response

During exercise, post-training, and resting, high-intensity physical exercise or competition triggered a proinflammatory response (Contrepois et al., 2020; Scheffer & Latini, 2020). However, the inflammatory response is a defence mechanism to protect athletes against infection or injury by localizing and eliminating the harmful agent and removing damaged tissue components to facilitate healing (Scheffer & Latini, 2020; Wang et al., 2020). Regular exercise had an anti-inflammatory effect, because leukocyte and lymphocyte counts decreased during exercise (Wang et al., 2020). Our study highlights that both groups had similar findings. However, CR regulated the immune response and improved the performance of immune cells (Lee & Dixit, 2020; Okawa et al., 2021). Thus, our findings show that CR does not alter the immune response.

The impact of CR on the immune response in athletes remains unclear. Studies have evaluated CR in non-athletes, where sustained −25% of CR for 2 years induced a notable reduction in white blood cells (Meydani et al., 2016). Other studies using energy restriction in amateur athletes for 20 weeks found a reduction of lymphocytes and an increase of white blood cells (Sarin et al., 2019). However, our investigation yields novel insights, underscoring that short-term CR regimens do not significantly affect white blood cell count, suggesting that immune parameters remain relatively unaffected in the context of brief CR episodes. These findings advance our understanding of the nuanced relationship between CR and immune function. Particularly, 6 weeks of CR could be a promising intervention to enhance the immune response in male professional soccer players and should be further investigated.

LDH is a blood biomarker of the inflammatory response and its concentration depends on the relative equilibrium between glycolytic rate, O_2, mitochondria muscle density, pyruvate metabolism, and NADH (Glancy et al., 2021). This correlation explains the peaks of LDH concentration after high-intensity exercise (Glancy et al., 2021) and maintenance of high concentration after exercise for a few days in the resting stage, as observed in soccer players without dietary intervention (Mohr et al., 2016; Silva et al., 2018; Souglis et al., 2015; Xin & Eshaghi, 2021). Our findings show a similarity in LDH concentrations between both groups, highlighting that LDH concentrations remain unchanged by CR.

Fatigue

Testosterone is an anabolic–androgenic steroid hormone that has multiple functions in regulating muscle mass, bone mass, and nervous system (Gharahdaghi et al., 2021). At the onset of physical activity, testosterone levels surge and then stabilize to baseline levels. Actual evidence indicates that testosterone levels remain largely unaffected by exercise (Gharahdaghi et al., 2021). Consistently, our findings indicate that testosterone homeostasis remains unchanged by CR. This has been corroborated in other studies with different dietary interventions and sport disciplines (Huovinen et al., 2015; J. J. Peos, Helms, Fournier, Ong, et al., 2021; Vidić et al., 2021).

Blood cortisol is conditioned by the intensity and duration of physical exercise (Scheffer & Latini, 2020). Cortisol increases during exercise and returns to baseline levels in the recovery period, corresponding to the bioenergetics process (Contrepois et al., 2020; Souglis et al., 2015). After long-term exercise, cortisol regulates the immune response (Scheffer & Latini, 2020; Wang et al., 2020). These metabolic changes could explain the uniformity of immune response in both groups in this study. Uniformity of cortisol balance was similar to other studies in jumpers, sprinters (Huovinen et al., 2015), and soccer players (Souglis et al., 2015). However, cortisol results differ from studies in Judo (Abedelmalek et al., 2015) and male weightlifter (Longland et al., 2016). These discrepancies are due to the direct relationship between cortisol level, body composition, and muscle mass (Calbet et al., 2017; Longland et al., 2016).

Studies in male soccer players without nutritional intervention (Field et al., 2023; Marqués-Jiménez et al., 2022; Peres et al., 2022; Souglis et al., 2015) found that urea plasma concentrations increased immediately after exercise due to decreased urea urinary excretion, increased muscle catabolism, and protein turnover. After 24–72 h, plasma urea values recover to baseline values of pre-match or pre-exercise (Field et al., 2023; Marqués-Jiménez et al., 2022; Souglis et al., 2015). Our findings signal a decrease in urea levels in CR and NC groups. These variations between studies could be due to differences in training session and inter-day, inter-week, season, position, and inter- and intra-individual variability of biomarkers (Alshuwaier et al., 2022; Becker et al., 2020; Nowakowska et al., 2019). In addition, urea recovery values can be a manifestation of protein metabolism adaptation and an indicator of recovery from fatigue (Marqués-Jiménez et al., 2022;

Nowakowska et al., 2019; Skorski et al., 2022). Therefore, our results reflect optimal recuperation of participants and preservation of physiological mechanism during recovery.

CPK is responsible for generating ATP, creatine for muscle contraction, and other energy-demanding processes (Silva et al., 2018). After exercise, the total serum activity of CPK increased and peaked at the end of exercise, and then decreased in the following 72 h (Silva et al., 2018). In this study, CPK decreased at 6 weeks and recovered to baseline values at 12 weeks. This was also observed in male volleyball athletes and football players after official matches (Barros et al., 2017; Berriel et al., 2020; Khaitin et al., 2021).

Physical performance

CMJ and SJ are reliable measures for power, strength, and speed in soccer (Nuñez et al., 2021; Rodríguez-Rosell et al., 2017). Our results indicated that CR, like NC, improved physical performance due to CR-induced physiological adaptations. *In vivo* studies have shown that CR can increase the quality and number of mitochondria in skeletal muscle, resulting in improved energy efficiency and physical performance (Chen et al., 2015; Kitaoka et al., 2016; Shirai et al., 2021). Other studies have demonstrated that CR can increase energy efficiency and physical performance after just 1 month of taekwondo and athletics (Capó et al., 2020; Pons et al., 2018). Overall, our results suggest that CR has a positive effect on physical performance through biological adaptations induced by CR.

Perceived exertion

Perceived exertion is a surrogate indicator to monitoring training load (Djaoui et al., 2017). The effect of dietary interventions on RPE in athletes has been scarcely studied. Our results agree with a study in which 10 competitive cyclists who completed a protocol of 3 weeks of CR (−40%) had significantly lower RPE after CR (Ferguson et al., 2009).

Final considerations

Despite the benefits of CR on physical performance, fatigue, inflammation, and immunity we recognized key aspects of implementing CR. Moderate and severe CR could decline cognitive behaviour and memory due to decreased blood glucose (Cherif et al., 2016; Zouhal et al., 2020). In players undergoing CR, short intervals to stop intervention or "*diet breaks*" are advisable. This strategy will allow for increased mental focus, decreased irritability, and increased sensation of fullness (J. J. Peos, Helms, Fournier, Krieger, et al., 2021).

Unplanned or severe CR can cause deficiency of essential nutrients, such as vitamins, minerals, amino acids, and fatty acids (Pons et al., 2018), which can negatively impact the physical performance and health of athletes (Pons et al., 2018). Moderate or severe CR (>30% with respect to REI) can negatively impact the metabolic, endocrine, cardiovascular, and muscular systems (Antonio Paoli et al., 2021; Ito et al., 2023; Thomas et al., 2016; Turocy et al., 2011). Therefore, CR should always be slightly limited (20%–30% of REI) and carefully planned to maximize its positive effects and avoid undesirable consequences (Pons et al., 2018; Thomas et al., 2016). In this study, a structured dietary plan was implemented to control for these aspects. We encourage researchers to monitor potential alterations.

Limitations and strengths

The principal strength of this study was that it investigated the effects of CR (−25% of REI) on elite male professional soccer players. This study has three limitations. First, sports performance in elite athletes could be influenced by other dietary factors that were not considered, for example, gut microbiota and caffeine intake (Guest et al., 2021; Marttinen et al., 2020). Second, our results were obtained during a CR of −25% REI; therefore, other degrees of CR could obtain different results. Third, although all players were encouraged to maintain their regular training program, physical activity was not controlled, making it difficult to compare the exercise level in future studies.

CONCLUSIONS

Our research has shown that implementing CR, 25% less than the REI, can be a suitable intervention for male professional soccer players to reduce perceived exertion. This intervention did not change biochemical parameters, such as cortisol, testosterone, urea, immune, or inflammatory response. To avoid cognitive decline, physical damage, and nutritional deficiencies, it is advisable to implement CR through a structured diet, diet breaks, and supervision. Studies should evaluate the combined effect of mild and moderate CR with other dietary factors.

AUTHOR CONTRIBUTIONS

Conceptualization, G. G., A. N., J. D .C., and C. T. G.; Data curation, G. G.; Formal analysis, G. D., and G. G.; Funding acquisition, G. G. Investigation, G. G., and A. N.; Methodology, G. G., J. D. C., and C. T. G. Project administration, G. G., and A. N. Resources, G. G.; Supervision, G. G., J. D. C., and C. T. G.; Validation, G. G.; Analysis, G. D., and G. G. Visualization, G. D. Writing – original draft, G. G. and G. D.; Writing – review & editing, all authors.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ETHICS APPROVAL

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The study followed ethical research practices and received approval from the research ethics committee at the Universidad Autónoma de Madrid (Autonomous University of Madrid) (CEI 100-1873) on June 21, 2019.

CONSENT TO PARTICIPATE

Informed consent was obtained from all individual participants included in the study.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, [GG], upon reasonable request.

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ORIGINAL ARTICLE

Analysis of speeds in the 400-meter hurdles and gender differences: A study from the Paris 2024 Olympics

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ABSTRACT

Background/objectives. This study aims to analyse the speed differences between men and women in the 400 meters during the Paris 2024 Olympic Games. Average speeds in each segment of the race were evaluated, highlighting gender variations and performance across the different rounds of the competition. Methods. A descriptive observational study was conducted using data from 208 athletes (50% women). Average speeds per 50-meter segments were analysed across all rounds (heats, semifinals, and final), applying Student's t-tests to compare results between genders. The significance level was set at $p < .05$. Results. The average speeds showed significant differences between sexes in all segments of the race ($p < .05$). The largest difference was observed in the first 150 meters, where men outpaced women by a margin of 0.97 km/h. By 250 meters, the difference decreased to 0.43 km/h. In the final rounds, the winners reached maximum speeds of 36.87 km/h (men) and 32.48 km/h (women). Conclusion. Men exhibit a biomechanical advantage in the race's early stages, while both sexes strategically adjust their pacing in the final rounds. These findings suggest that gender differences in performance are linked to both physiological and biomechanical factors.
Keywords: Performance analysis, Competitive analysis, Biomechanics, Gender performance metrics, Olympic event outcomes, Endurance racing strategies.

Cite this article as:
de Souza-Lima, J., Giakoni-Ramírez, F., Muñoz-Strale, C., Yáñez-Sepúlveda, R., Duclos-Bastias, D., Cortés-Roco, G., Bonilla, D. A., Olivares-Arancibia, J., & Valdivia-Moral, P. (2025). Analysis of speeds in the 400-meter hurdles and gender differences: A study from the Paris 2024 Olympics. *Journal of Human Sport and Exercise, 20*(2), 435-445. https://doi.org/10.55860/fptent35

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Submitted for publication November 04, 2024.
Accepted for publication December 17, 2024.
Published February 10, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/fptent35

INTRODUCTION

Athletics has been a central field of study in research on human physical abilities for decades, with speed events playing a crucial role in understanding sports performance (Jeffreys, 2024; Paul et al., 2016). Among these events, the 400-meter sprint stands out as one of the most challenging, requiring a unique combination of explosive speed and sustained endurance. This event draws attention not only due to its physiological complexity but also because of the performance differences observed between elite athletes of different sexes (Guex, 2012; McClelland & Weyand, 2022).Previous research has identified significant differences in the performance of male and female athletes in sprint events, particularly in shorter distances such as the 100 and 200 meters (Atkinson et al., 2024; Zhang et al., 2021). Specifically, men tend to reach higher maximum speeds due to differences in muscle mass, power output, and anaerobic capacity. However, the 400-meter event introduces an additional variable: the athletes' ability to maintain speed over a longer distance, which requires a complex interaction between anaerobic and aerobic systems (Iskra et al., 2024).

In this context, the Paris 2024 Olympic Games provided a unique opportunity to study the performance of elite athletes under peak competitive conditions. Sex differences in the 400-meter performance during the Olympics have yet to be explored in depth, despite the significance of this event in the Olympic program. This analysis is crucial for understanding how the physiological characteristics of men and women impact their performance in races that demand both speed and endurance (Iskra et al., 2024; Santisteban et al., 2022).

Performance in the 400 meters is intrinsically linked to how efficiently athletes can utilize their energy systems (Le Hyaric et al., 2024). Research has shown that while women have a lower capacity for producing maximum power, they tend to be more efficient in utilizing the aerobic system during longer-distance races (Miller, 2023; Santisteban et al., 2022; Tiller et al., 2021). This suggests that the performance differences between men and women in the 400 meters may be more related to energy efficiency than pure speed (Helgerud et al., 2023).

Therefore, this study aims to analyse the differences in running speed between male and female athletes in the 400 meters during the Paris 2024 Olympic Games. Through a detailed analysis of speed variations across different race segments, the study seeks to provide new insights into current gender differences and their influence on performance in this Olympic event, contributing to the development of specific training programs.

MATERIAL AND METHODS

Study design

This descriptive observational study is based on performance data from 208 speed records of athletes who participated in the 400-meter event during the Paris 2024 Olympic Games.

Participants

The dataset includes 104 records from female athletes and 104 from male athletes. Since some athletes competed in multiple rounds (heats, semifinals, and finals), the same athletes may be represented more than once in the dataset.

Inclusion and exclusion criteria

The inclusion criteria required athletes to be officially registered in the 400-meter event. Exclusion criteria included failure to start the race, sustaining an injury during the race, or finishing the race by walking. Based on these criteria, 2 female athletes and 13 male athletes were excluded from the study.

Ethical considerations

This study adheres to the principles of the Declaration of Helsinki (World Medical Association, 2013), ensuring ethical conduct and transparency in data collection and analysis. Obtaining informed consent was not required since the data is publicly available and does not involve direct interventions with participants.

Procedures

Information for each race segment (50 m, 100 m, 150 m, etc.) was extracted directly from the official Olympics website (Olympics, 2024). The split times for each segment were downloaded in PDF format and subsequently input into an Excel template for analysis. The results included time and average speed measurements for each round and by gender. This approach enabled a detailed analysis of the athletes' performance and provided a solid foundation for the statistical interpretation of the results obtained during the Olympic competition.

Statistical analysis

A comparative analysis of running speeds between men and women was conducted. Average speeds per 50-meter segment were calculated for each gender across all rounds of the competition, including heats, semifinals, and finals, using the formula ($v = d/t$). The data was organized into tables displaying the means and standard deviations of the average speeds for each race segment. To assess gender differences in speed, independent samples t-tests were applied. The significance level was set at $p < .05$. The graphical analysis was performed in Google Colab®, utilizing the Matplotlib and Pandas libraries in Python to generate visualizations comparing athlete performance across each round. The comparisons covered all stages of the competition, including heats, repechages, semifinals, and the final. The collected data was processed using Jamovi software, version 2.3.21, where average speeds were calculated from the recorded times. These speeds were first calculated in meters per second and then converted to kilometres per hour for more detailed analysis. Additionally, a heatmap of Bonferroni-adjusted *p*-values was generated to evaluate the statistical significance of the differences in speeds across various distances. This allowed for identifying which distance comparisons showed statistically significant differences after the adjustment was applied.

RESULTS

Of the 208 participants, 50% were women. The comparative analysis of average speeds in the 400-meter race revealed significant differences between men and women across all segments ($p < .05$). In the first 150 meters, men recorded an average speed 0.97 km/h higher than women, representing the largest difference observed throughout the race. As the distance progressed, these differences diminished, reaching 0.43 km/h at 250 meters. The final speeds of the male and female winners also reflected a significant increase as they advanced through the rounds, with the highest performance observed in the final round. These differences in speed between genders suggest an advantage for men in the early stages of the race, while both sexes demonstrated strategic pacing adjustments in the final rounds.

Table 1 presents the average speeds and times of athletes throughout the 400 meters, divided into 50-meter segments. The values are shown separately by gender and across the different rounds of the competition, including heats, repechage, semifinals, and the final.

Table 2 shows the average speeds (in kilometres per hour) of athletes in different segments of the 400-meter race, broken down by gender and round. The columns represent the speeds reached in the 50, 100, 150, 200, 250, 300, 350, and 400-meter segments.

Table 1. General characteristics of average times and speeds in 400 meters by gender and round.

Gender	Round	Athletes (n)	Average Time (s)	Speed (km/h)
Female	Final	8	27.0 ± 0.3	29.5 ± 0.4
Female	Semi 3	8	27.6 ± 0.4	28.7 ± 0.4
Female	Semi 2	8	27.7 ± 0.4	28.8 ± 0.4
Female	Semi 1	8	27.5 ± 0.5	28.7 ± 0.6
Female	Repechage 4	6	28.1 ± 0.3	28.2 ± 0.2
Female	Repechage 3	7	28.1 ± 0.3	28.2 ± 0.9
Female	Repechage 2	7	28.3 ± 0.3	28.0 ± 0.3
Female	Repechage 1	6	28.1 ± 0.2	28.2 ± 0.2
Female	Serie 6	7	28.0 ± 0.6	28.1 ± 0.5
Female	Serie 5	8	28.1 ± 0.5	28.3 ± 0.6
Female	Serie 4	8	27.7 ± 0.3	28.6 ± 0.3
Female	Serie 3	8	27.9 ± 0.5	28.4 ± 0.6
Female	Serie 2	7	27.9 ± 0.3	28.5 ± 0.4
Female	Serie 1	8	27.9 ± 0.4	28.5 ± 0.4
Male	Final	8	24.3 ± 0.4	32.9 ± 0.6
Male	Semi 3	8	24.5 ± 0.3	32.5 ± 0.3
Male	Semi 2	8	24.5 ± 0.3	32.6 ± 0.4
Male	Semi 1	8	26.4 ± 4.9	31.7 ± 2.3
Male	Repechage 4	6	25.1 ± 0.1	32.0 ± 0.3
Male	Repechage 3	6	25.0 ± 0.1	32.0 ± 0.2
Male	Repechage 2	7	25.3 ± 0.1	31.7 ± 0.1
Male	Repechage 1	7	25.2 ± 0.1	31.7 ± 0.2
Male	Serie 6	8	25.0 ± 0.2	32.0 ± 0.3
Male	Serie 5	8	24.9 ± 0.3	32.0 ± 0.4
Male	Serie 4	7	24.8 ± 0.4	32.2 ± 0.7
Male	Serie 3	8	24.8 ± 0.3	32.1 ± 0.3
Male	Serie 2	8	24.7 ± 0.2	32.4 ± 0.4
Male	Serie 1	7	25.0 ± 0.2	32.0 ± 0.3

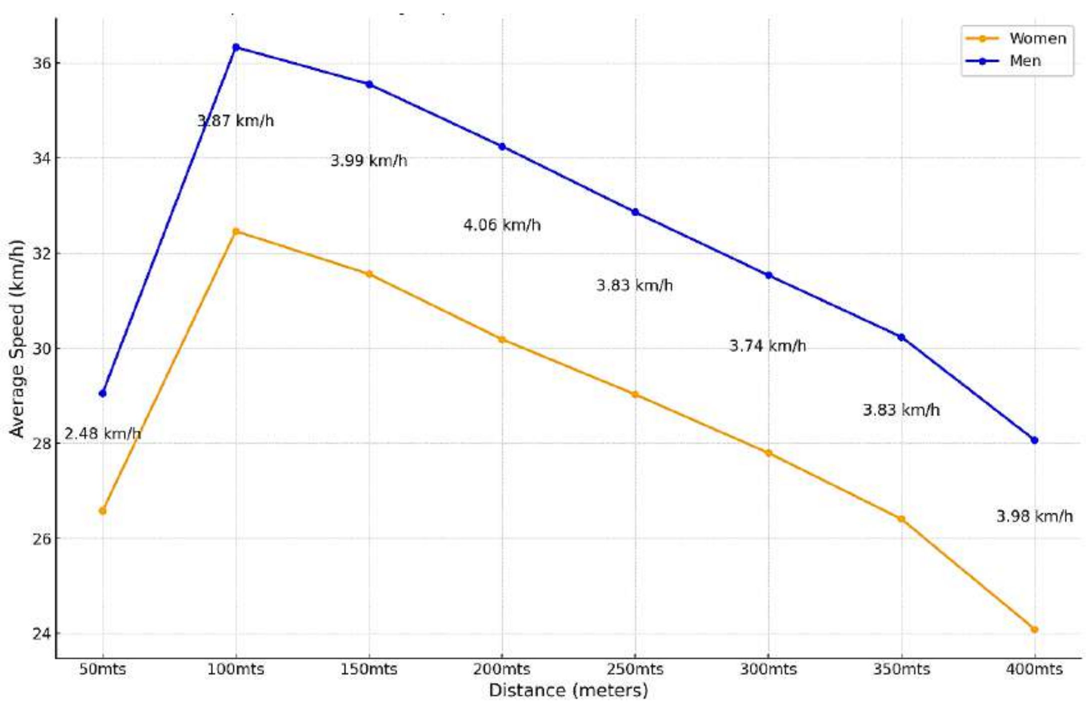

Figure 1. Comparison of average speeds between women and men across distances.

Table 2. Average (km/h) in different segments of the 400 meters: analysis by sex and round.

Gender	Round	50mts	100mts	150mts	200mts	250mts	300mts	350mts	400mts
Female	Final	27.3 ± 0.4	33.3 ± 0.5	32.6 ± 0.6	31.3 ± 0.5	29.8 ± 0.7	28.5 ± 0.6	27.6 ± 0.6	25.4 ± 0.7
Female	Semi 3	26.8 ± 0.5	32.6 ± 0.5	31.9 ± 0.5	30.5 ± 0.6	29.2 ± 0.5	27.7 ± 0.5	26.6 ± 0.6	24.4 ± 0.7
Female	Semi 2	26.6 ± 0.5	32.4 ± 0.6	31.7 ± 0.7	30.4 ± 0.4	29.0 ± 0.3	28.1 ± 0.3	27.0 ± 0.5	25.2 ± 0.8
Female	Semi 1	27.1 ± 0.4	33.0 ± 0.5	32.3 ± 0.6	30.6 ± 1.6	29.6 ± 1.9	27.7 ± 0.7	26.1 ± 0.6	23.5 ± 1.1
Female	Repechage 4	26.3 ± 0.3	32.2 ± 0.2	31.1 ± 0.3	29.8 ± 0.2	28.8 ± 0.2	27.6 ± 0.4	26.0 ± 0.7	23.6 ± 0.6
Female	Repechage 3	26.1 ± 0.2	32.0 ± 0.5	31.1 ± 0.4	29.9 ± 0.3	28.6 ± 0.4	27.3 ± 0.7	26.0 ± 0.9	23.9 ± 0.9
Female	Repechage 2	26.4 ± 0.6	32.1 ± 0.9	31.6 ± 0.6	30.2 ± 0.5	28.8 ± 0.2	27.7 ± 0.6	26.0 ± 1.3	23.7 ± 1.8
Female	Repechage 1	26.2 ± 0.3	32.0 ± 0.5	30.8 ± 0.3	29.8 ± 0.4	28.9 ± 0.5	27.7 ± 0.5	26.2 ± 0.6	24.2 ± 0.6
Female	Serie 6	26.8 ± 0.6	32.6 ± 0.8	31.5 ± 0.8	30.0 ± 0.6	28.1 ± 1.7	28.0 ± 1.8	25.6 ± 1.1	22.5 ± 0.8
Female	Serie 5	26.3 ± 0.6	32.1 ± 0.5	31.2 ± 0.7	29.9 ± 0.7	28.8 ± 0.8	27.7 ± 0.9	26.3 ± 1.0	24.2 ± 1.0
Female	Serie 4	26.4 ± 0.5	32.5 ± 0.2	31.7 ± 0.3	30.6 ± 0.3	29.7 ± 1.0	27.8 ± 1.0	26.2 ± 0.5	24.2 ± 0.9
Female	Serie 3	26.7 ± 0.6	32.4 ± 0.9	31.3 ± 1.0	30.0 ± 0.9	28.8 ± 0.5	27.5 ± 0.5	26.7 ± 2.1	23.6 ± 1.6
Female	Serie 2	26.5 ± 0.5	32.3 ± 0.5	31.2 ± 0.3	29.8 ± 0.4	29.0 ± 0.3	28.2 ± 0.6	26.5 ± 0.8	24.3 ± 0.9
Female	Serie 1	26.6 ± 0.5	32.7 ± 0.6	31.3 ± 0.5	29.7 ± 0.4	29.2 ± 1.0	27.6 ± 0.9	26.5 ± 0.7	24.3 ± 1.0
Male	Final	29.5 ± 0.7	37.3 ± 0.8	36.5 ± 1.0	35.0 ± 0.9	33.3 ± 0.9	32.0 ± 0.8	30.7 ± 1.0	29.0 ± 1.3
Male	Semi 3	29.6 ± 0.3	37.2 ± 0.6	36.4 ± 0.6	34.7 ± 0.5	32.7 ± 0.7	31.4 ± 0.6	30.1 ± 0.5	27.9 ± 0.7
Male	Semi 2	29.4 ± 0.4	36.8 ± 0.7	36.1 ± 0.4	34.8 ± 0.4	33.5 ± 0.4	31.6 ± 0.4	30.2 ± 0.4	28.5 ± 0.9
Male	Semi 1	29.2 ± 0.6	36.4 ± 0.6	35.5 ± 1.0	34.5 ± 0.8	33.3 ± 0.6	31.3 ± 1.4	27.3 ± 9.4	26.0 ± 8.6
Male	Repechage 4	28.5 ± 0.4	35.6 ± 0.4	34.7 ± 0.3	33.7 ± 0.4	32.5 ± 0.6	31.6 ± 0.6	30.6 ± 0.4	28.9 ± 0.6
Male	Repechage 3	28.9 ± 0.3	35.7 ± 0.6	34.6 ± 0.2	33.6 ± 0.2	32.7 ± 0.4	31.8 ± 0.3	31.2 ± 1.5	27.7 ± 1.3
Male	Repechage 2	28.6 ± 0.4	35.2 ± 0.7	34.1 ± 0.4	33.3 ± 0.1	32.5 ± 0.4	31.5 ± 0.5	30.2 ± 0.3	28.5 ± 0.3
Male	Repechage 1	28.6 ± 0.2	35.4 ± 0.6	35.3 ± 0.5	33.8 ± 0.3	32.0 ± 0.3	31.1 ± 0.6	29.7 ± 0.9	27.5 ± 1.1
Male	Serie 6	28.8 ± 0.6	36.2 ± 0.6	35.5 ± 0.5	34.1 ± 0.4	32.6 ± 0.2	31.2 ± 0.5	29.7 ± 0.8	27.5 ± 1.0
Male	Serie 5	29.2 ± 0.6	36.3 ± 0.5	35.4 ± 0.5	33.9 ± 0.4	32.5 ± 0.4	31.0 ± 0.4	30.0 ± 0.7	27.6 ± 1.2
Male	Serie 4	28.7 ± 0.5	36.4 ± 0.9	35.7 ± 0.7	34.5 ± 0.5	33.1 ± 0.5	31.6 ± 0.6	30.3 ± 0.7	27.4 ± 2.9
Male	Serie 3	29.1 ± 0.3	36.4 ± 0.8	35.4 ± 0.6	34.1 ± 0.4	32.8 ± 0.4	31.5 ± 0.4	30.2 ± 0.5	27.6 ± 0.6
Male	Serie 2	29.1 ± 0.4	36.3 ± 0.6	35.9 ± 0.6	34.6 ± 0.7	33.2 ± 0.5	31.7 ± 0.5	30.2 ± 0.7	28.1 ± 1.1
Male	Serie 1	28.8 ± 0.5	36.0 ± 0.7	35.4 ± 0.4	34.0 ± 0.5	32.6 ± 0.6	31.6 ± 0.4	29.9 ± 0.5	27.6 ± 0.6

Figure 1 illustrates the average speed differences between men and women in each segment of a 400-meter race, considering all rounds. The figure shows that men consistently maintain higher speeds than women across all segments of the race. The most pronounced differences occur in the first 150 meters, where the speed gap reaches its peak. As the race progresses, these differences slightly decrease but remain consistently in favour of the men throughout the entire race.

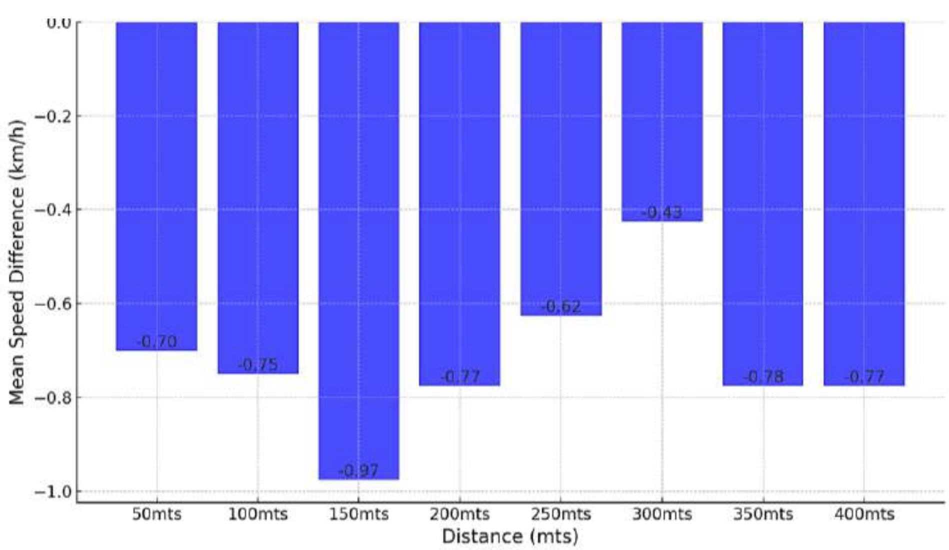

Figure 2. Mean speed differences between men and woman by distance (all rounds).

Figure 2 displays the average speed differences between men and women in each 50-meter segment of a 400-meter race, considering all rounds. The bars indicate that men run faster than women across all segments of the race. The most pronounced difference is observed in the 150-meter segment, where men's average speed exceeds women's by 0.97 km/h. As the race progresses, the speed difference slightly decreases but remains steady at around 0.77 km/h in the final segments of the race.

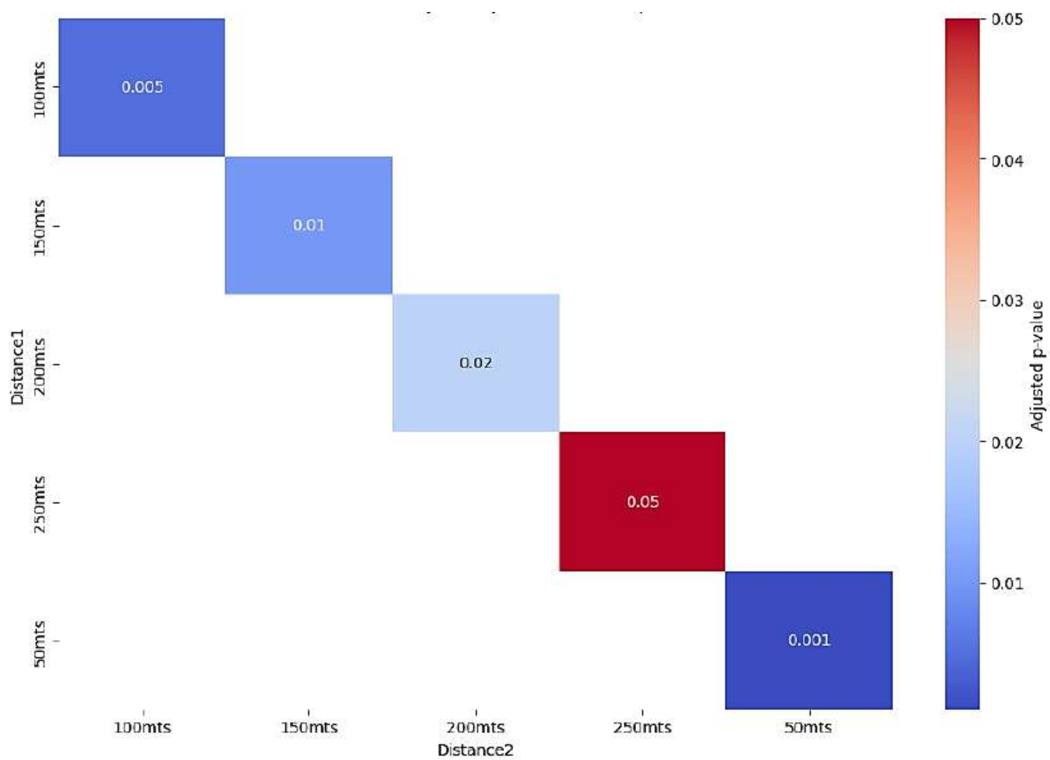

Figure 3. Heatmap of Bonferroni adjusted *p-values* for velocity differences across distances.

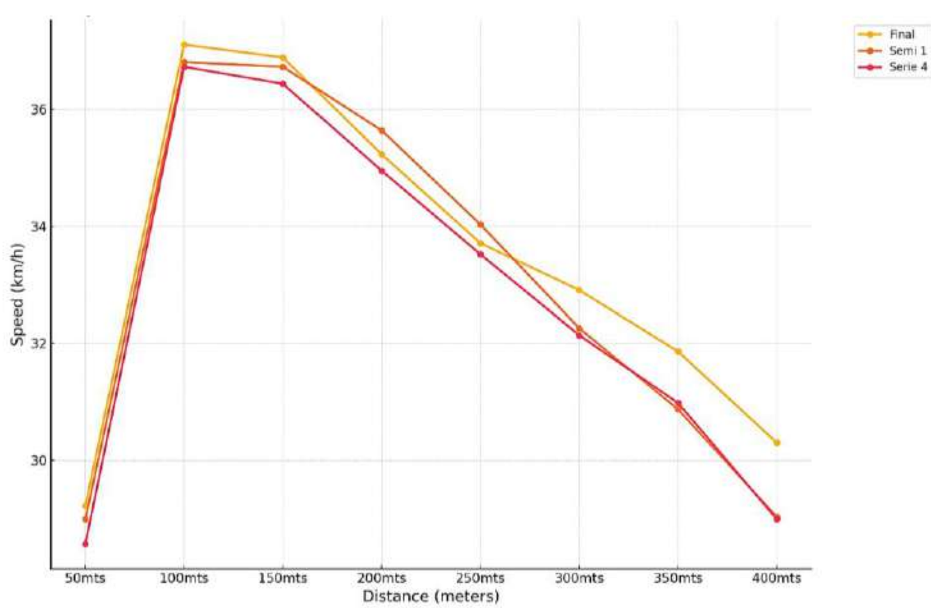

Figure 4. Speed evolution of de male winner (Hall Quincy) across rounds and distances.

Heatmap 3 displays Bonferroni-adjusted *p*-values, highlighting the statistically significant differences in average speeds across various distances. Blue cells indicate comparisons with low *p*-values, such as between 50 and 100 meters, which are statistically significant, while red cells, such as between 250 and 50 meters, indicate less significant comparisons.

Figure 4 illustrates the speed evolution of the male winner (Hall Quincy) across different segments of the 400-meter race throughout the rounds (Heat 4, Semifinal 1, and Final). It shows that Quincy generally reached his highest speeds in the final, particularly in the first 150 meters, where his speed exceeded 36 km/h. After this point, his speed began to decline similarly in all rounds, showing a progressive deceleration towards the 400-meter mark. Comparing the different rounds, a performance improvement is evident in the final compared to the heats and semifinals.

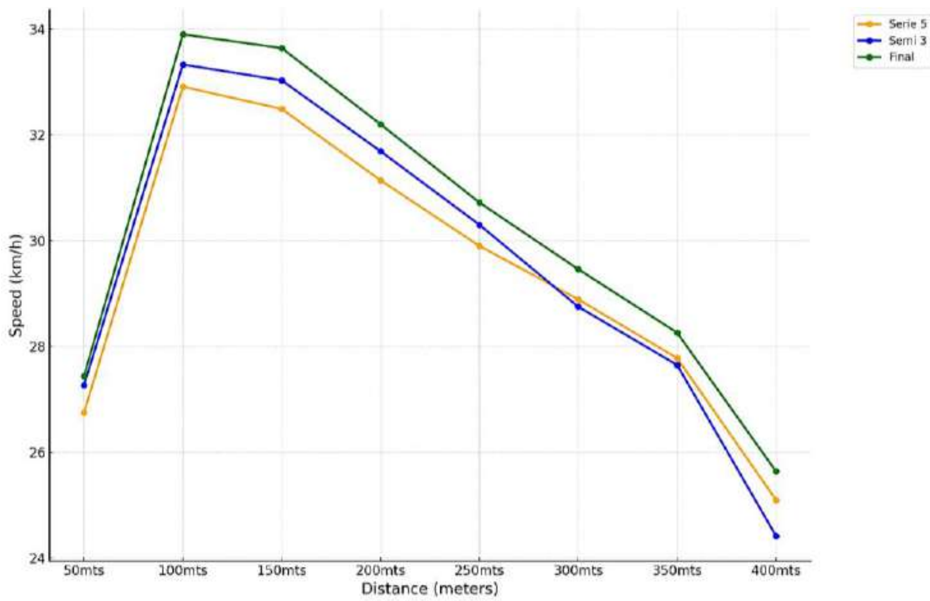

Figure 5. Speed evolution of de female winner (Marileidy Paulino) across rounds and distances.

Figure 5 illustrates the speed evolution of the female winner across different segments of the 400-meter race throughout the rounds (Heat 5, Semifinal 3, and Final). It shows that Marileidy reached her highest speeds in the final, with a peak speed of approximately 34 km/h in the first 150 meters. After this point, her speed progressively declined throughout the race in all rounds. However, an improvement in her performance is evident in the final compared to the preliminary rounds (Heat and Semifinal), where she maintained higher speeds during the race.

DISCUSSION

It was observed that the average speed progressively decreases as athletes advance through the total distance of the race, with the most pronounced speed differences occurring in the first 150 meters, particularly between men and women. Previous studies indicate that elite athletes reach maximum speeds of 10.12 m/s for men and 8.96 m/s for women between the 50 and 100-meter segments. We converted these values to kilometres per hour (km/h) using the formula 1 m/s = 3.6 km/h, resulting in 36.43 km/h for men and 32.26 km/h for women. In our study, the maximum speeds were 36.87 km/h for men and 32.48 km/h for women, aligning with the reported values. Additionally, we observed an average fatigue index of 22.99% in elite runners, similar to previous findings, suggesting that elite athletes adopt an aggressive pacing strategy, experiencing a greater drop in speed over the final 100 meters. These findings reinforce the importance of physiological and biomechanical factors in maintaining performance, even under conditions of advanced fatigue (Hanon & Gajer, 2009).

In 400-meter race performance, energy systems play a key role in the interaction between anaerobic and aerobic metabolism. According to other authors, energy for these races is derived 59% from the anaerobic system and 41% from the aerobic system for men. In the case of women, this ratio is 55% and 45%, respectively (Duffield et al., 2005). Our findings align with these results, as we observed a strong reliance on anaerobic reserves during the first half of the race, followed by an increased aerobic contribution towards the end, when fatigue begins to set in. In our study, elite runners reached maximum speeds of 36.87 km/h for men and 32.48 km/h for women in the first 100 meters. However, by the end of the race, speed declined due to lactate accumulation and reduced phosphocreatine (PCr), as noted by Dall Pupo et al. The balance between these metabolic pathways, along with the capacity for muscle recruitment and the body's buffering ability to manage anaerobic byproducts, allows athletes to maximize their performance during the sprint (Dal Pupo et al., 2013).

As mentioned earlier, the anaerobic system is more heavily utilized in men (59%) than in women (55%). Although both sexes exhibit similar patterns of speed reduction, men tend to maintain a higher average speed across all distances, highlighting significant physiological differences between genders. This finding is consistent with previous studies indicating that elite athletes optimize their effort distribution, sustaining high speeds until the final segments of the race, where metabolic conditions, such as lactate accumulation and reduced muscle pH, significantly impact performance. In this context, it has been reported that blood lactate levels can reach up to 20.5 mmol/L in 400-meter runners, contributing to muscle fatigue and impairing the muscles' ability to maintain efficient contraction (Cicchella, 2022). These metabolic factors partly explain why; despite exhibiting similar patterns of speed reduction, men are able to maintain higher speeds, likely due to a greater capacity to manage acidosis and the fatigue resulting from lactate accumulation.

It is important to highlight that the greatest speed reduction between men and women occurs in the first 150 meters, with a difference of -0.97 km/h. This phenomenon may be related to male runners' ability to maintain a better balance between stride frequency and stride length during the early stages of the race. Previous research indicates that elite runners tend to reach their peak stride frequency between the first 50 and 100 meters, while stride length peaks between 100 and 150 meters, suggesting a biomechanical advantage for men in these key segments of the race (Gajer et al., 2007). In contrast, in women, stride frequency tends to decrease more rapidly as muscle fatigue accumulates, affecting their performance in the later segments of the race (Guex, 2012). These findings underscore the significant biomechanical and physiological differences between the sexes during the 400-meter race.

In terms of comparison between male and female winners, it is observed that men are able to maintain more consistent performance across the different rounds, suggesting better effort management and greater resistance to fatigue. This may be related to differences in lactate accumulation, which in male 400-meter runners can reach up to 17.3 mmol/L, indicating a higher capacity to tolerate acidosis compared to women (Kalih & Rahmadani, 2021). In contrast, although women also manage to maintain similar speeds across rounds, their speed decline is more pronounced in the second half of the race due to greater muscle fatigue. This is consistent with previous studies, which showed that asymmetric muscle activity and fatigue in the lower limbs significantly increase during the second half of the race, affecting mechanical efficiency and performance in female athletes (Iwańska et al., 2021).

The findings of the present study limit the complete verification of the analyses of the 400 meters. However, a theoretical and explanatory influence of fatigue and lactate accumulation on performance, particularly during the final phases of the race, was observed. This influence appears to be linked to differences in the anaerobic and aerobic systems' capacity to sustain speed, resulting in a greater negative impact on women, especially in the later segments of the race. Although the results suggest a greater ability in men to manage acidosis and maintain biomechanical efficiency, further research is needed to confirm these findings. Future studies should focus on analysing the precise interactions between muscle activity and kinematic variables throughout the entire race, especially concerning effort distribution and muscle fatigue. These results highlight the importance of optimizing both the energetic and biomechanical aspects of training to maximize performance in this demanding discipline.

One of the main limitations of this study is the lack of control over individual variables, such as differences in training experience, body composition, and muscle fibre distribution among the participants, which may have influenced the observed performance. Additionally, the sample focused on elite runners, limiting the generalizability of the results to athletes at other performance levels. Future studies could benefit from a more diverse sample and a more detailed focus on the individual characteristics that affect the physiological and biomechanical response during 400-meter races.

CONCLUSION

In this study, it was determined that elite runners participating in the 400-meter event primarily rely on the anaerobic system during the first half of the race, followed by a greater aerobic contribution towards the end. We observed that men are able to maintain higher speeds than women, likely due to better management of acidosis and muscle fatigue. Additionally, men sustain a better balance between stride frequency and stride length in the early stages of the race, contributing to their superior performance compared to women, who experience a greater decrease in speed during the second half. These findings highlight key differences in the physiological and biomechanical strategies between the sexes.

AUTHOR CONTRIBUTIONS

Study concept and design: JSL, RYS PVM; Search strategy: JSL and DB; Literature identification and selection: JSL, GCR, JOL and FGR; Data extraction and quality assessment: JSL, FGR, DDB; Narrative synthesis: PVM, JSL and DB; Manuscript writing: JSL, RYS, GCR , JOL and PVM; Study supervision: FGR, DB, PVM, CMS, RYS. FGR conceived the study, participated in its design and coordination, and contributed to manuscript writing. All authors read and approved the final version of the manuscript.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Decoding the influence of field surface, tactical positioning, and field zone on tactical networks in youth football

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ABSTRACT

This study investigates the impact of different field surfaces on passing networks and tactical performance of youth football teams. Using observational analysis, tactical positioning data were collected, and passing networks were constructed. The results suggest differences in network metrics based on the surface type: average shortest path length F(2.052) = 6.099; $p < .006$, $\eta^2 = 0.289$; betweenness centrality F(2.001) = 7.294; $p < .003$, $\eta^2 = 0.327$; closeness centrality F(2.025) = 5.207; $p < .011$, $\eta^2 = 0.258$; clustering coefficient F(2.032) = 23.679; $p < .001$, $\eta^2 = 0.612$; and radiality F(2.001) = 6.099; $p < .006$, $\eta^2 = 0.289$. Closeness centrality varied significantly between tactical positions F(10.009) = 1.918, $p < .05$, $\eta^2 = 0.466$. Passing relationships based on field zones also showed significant differences: average shortest path length F(23.193) = 6.057; $p < .001$, $\eta^2 = 0.744$; betweenness centrality F(23.002) = 5.103; $p < .001$, $\eta^2 = 0.710$; closeness centrality F(23.015) = 6.835; $p < .001$, $\eta^2 = 0.766$; degree F(23.592) = 5.298; $p < .001$, $\eta^2 = 0.717$; radiality F(23.001) = 8.366; $p < .001$, $\eta^2 = .800$; and stress F(23.773) = 5.302; $p < .001$, $\eta^2 = 0.718$. This study provides valuable insights for coaches and analysts on optimizing youth soccer performance, highlighting the importance of considering field surface in tactical planning and training strategies.

Keywords: Performance analysis, Youth football, Passing networks, Field surfaces, Tactical performance, Network metrics.

Cite this article as:
Brito, Â., & Freitas, L. (2025). Decoding the influence of field surface, tactical positioning, and field zone on tactical networks in youth football. *Journal of Human Sport and Exercise, 20*(2), 446-458. https://doi.org/10.55860/e8rafc81

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Submitted for publication November 21, 2024.
Accepted for publication January 08, 2025.
Published February 10, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/e8rafc81

INTRODUCTION

In recent years, the analysis of passing networks has emerged as an innovative and effective approach to understanding the dynamics of football. These networks provide a visual and quantitative representation of player interactions, offering valuable insights into team organization and game strategy (Alves et al., 2022; Clemente et al., 2015; Pina et al., 2017; Gonçalves et al., 2017). The application of network analysis techniques in team sports, particularly football, has gained prominence in the scientific literature, standing out as a crucial tool for coaches, analysts, and researchers. Various network metrics can be used to provide a comprehensive view of the structure and functionality of passing networks, offering a detailed and informative analysis (Assunção et al., 2022; Clemente et al., 2020; Mendes et al., 2028; Sarmento et al., 2014). However, the type of field surface on which games are played can significantly influence these dynamics.

For example, Bartlett et al. (2012) examined the use of network analysis in the study of the collective behaviour of football teams, demonstrating how these techniques can identify tactical and movement patterns. Passos et al. (2011) used network analysis to explore the dynamics of interaction between players in elite games, demonstrating the relevance of these techniques for understanding cooperation and coordination on the field.

Furthermore, Clemente et al. (2015) investigated the application of network analysis to assess team centrality and cohesion, emphasizing the importance of these metrics in evaluating collective performance. The study by Peña and Touchette (2012) reinforced the utility of passing networks for understanding the fluidity and efficiency of offensive transitions in football, providing insights into the tactical organization of teams.

More recently, the work of Ribeiro et al. (2020) highlighted how network analysis can be used to identify key players and evaluate the tactical structure of teams in different competitive contexts, demonstrating the evolution and sophistication of these techniques in performance analysis in football.

It is expected that the type of playing surface can significantly influence these dynamics. The influence of the type of field surface on the performance of players and teams has been the subject of numerous studies over the years, revealing significant variations in game characteristics according to the surface. According to Vaeyens et al. (2008) the type of field can affect not only the physical performance of players but also the strategy adopted by teams.

Artificial turf, natural grass, and clay football field have distinct characteristics that can alter ball speed, traction, and the physical wear on athletes. Artificial turf, a more uniform surface developed to simulate the conditions of natural grass, has particularities that, according to Andersson et al. (2008), can lead to a higher risk of injuries due to increased resistance and traction. Additionally, artificial turf tends to be faster, influencing the dynamics of the game and how passes are executed. On the other hand, natural grass fields are widely preferred by players and coaches due to their softness and lower impact on athletes' joints. According to Ekstrand et al. (2011), natural grass offers a more traditional game with a lower risk of serious injuries, although it requires more maintenance, leading to variations in surface quality throughout the season. Regarding clay football fields, although less common in high-level competitions, they are still used in various regions and contexts. This type of surface is harder and more irregular, which can affect the accuracy of passes and ball control, consequently impacting the game's fluidity. According to Brito et al. (2017), clay football field influence running activity and players' technical actions. Additionally, Mendiguchia and Buchheit (2016) suggest that nature of the playing surface can significantly influence the athletes´ risk of injury, demonstrating that uneven field conditions or those with less traction can increase physical wear and tear and the likelihood of trauma, especially those related to falls and twists.

Consequently, given the scarcity of studies that have investigated the dynamics and efficiency of passing networks on different field surfaces, it becomes relevant to assess the effect of the field surface on the passing relationships established by players. The choice of field type has direct implications on team performance and the analysis of passing networks. Understanding the physical and mechanical characteristics of each type of surface is essential for adopting effective game strategies.

To analyse the structure and functionality of passing networks in football, we can use several network analysis metrics, each offering specific insights into the dynamics and efficiency of the network. The degree metric is used to identify important nodes (hubs) in the network, while Closeness Centrality measures how close a node is to all other nodes in the network, highlighting strategic nodes in the spread of the ball. Betweenness Centrality evaluates how often a node appears on the shortest paths between other nodes, identifying crucial players in the mediation and transition of the game. The Clustering Coefficient analyses the formation of clusters or communities within the network, reflecting tactical and organizational cohesion. Average Shortest Path Length evaluates the overall efficiency of the network by measuring the average distance of the shortest paths between all pairs of nodes, indicating faster and more efficient ball transfer. Additionally, Stress measures a node's load, providing additional insights into the player's importance and influence in the network, while Radiality analyses a node's position relative to the network periphery, offering insight into efficiency.

Therefore, the objective of this study is to investigate how different field surfaces (artificial grass, natural grass and clay football field) influence the structure and functionality of passing networks in football. Specifically, the study aims to: (i) Evaluate how the centrality of players in the passing networks varies depending on the field surface, the tactical positioning of the players and the zone field, using metrics such as Degree, Closeness Centrality and Betweenness Centrality; (ii) Measure the tactical cohesion of teams on different field surfaces through the Clustering Coefficient and the Average Shortest Path Length; (iii) Determine the efficiency of pass networks in terms of speed and accuracy, considering the Stress and Radiality variables; (iv) and Identify and compare movement patterns and strategies adopted by teams on different field surfaces, observing differences in game dynamics and passing execution.

With this study, it is expected to provide an in-depth understanding of the implications of different field surfaces in football, contributing to the optimization of game strategies and improved team performance.

METHODS

Participants

Sixty male (under-14) football players (age: 13.4 ± 0.5; height: 161.82 ± 7.52; weight: 50.79 ± 7.22) with the same competitive level (playing and training 3.5 ± 1.4 years). All players and their guardians were informed about the research procedures, requirements, benefits and risks, and, in writing, consented to participate. The study protocol followed the guidelines established in the Declaration of Helsinki and was approved by the local Ethics Committee.

Experimental design

During three weeks, always on Sunday, the games were performed in the following conditions: week (1): 3 games on artificial turf; week (2): 3 games on natural grass; week (3): 3 games on clay football field. The teams and players who participated in the study were always the same and all football matches were played using 1-4-3-3 tactical structure, the most frequent in Portuguese youth teams (Rebelo et al., 2014). The players were classified according to their tactical position: 1 = goalkeeper (GK); 2 = right back (RB); 3 = right centre back (RCB); 4 = left centre back (LCB); 5 = left back (LB); 6 = central defensive midfielder (CDM); 7 = right centre midfielder (RCM); 8 = left centre midfielder (LCM); 9 = sticker (ST); 10 = right winger (RW); 11 = left winger (LW). The matches were played according to football rules, except match duration (30min, without breaks) and players' substitution (not allowed). The pitch size was adjusted to standardize the measure for all conditions (length: 100 m, width: 64 m). All matches were proceeded by a planned, standardised warm up of 15 min comprising running activities, small-sided games and stretching. Following this period, the players simulated a match during two periods of 2 min, interspersed by 1 min of passive recovery. All games were played between 9 and 11 a.m., with purpose of controlling the effects of circadian variations (Dellal et al., 2012).

The distribution of corridors and sectors can be visualized through the field diagram in Figure 1.

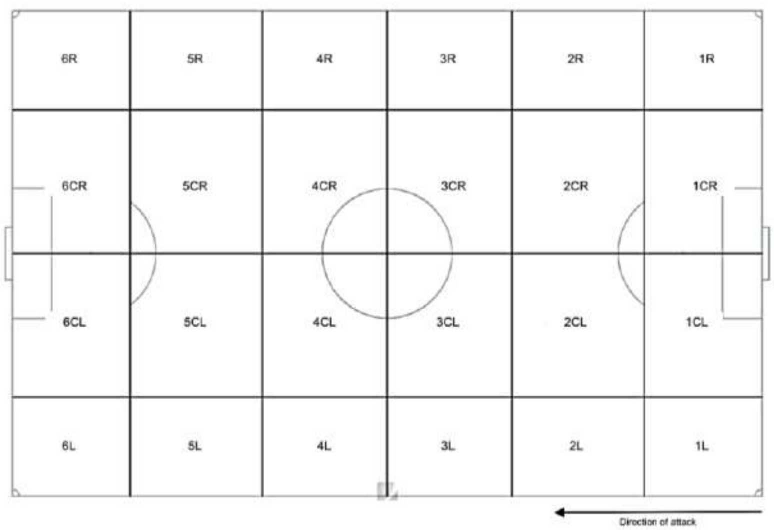


Figure 1. Field diagram (adapted from Amisco).

Data collection

The data were collected from football matches played on different field surfaces: artificial turf, natural grass, and clay football field. Each match was analysed to extract passing network metrics such as Degree, Closeness Centrality, Betweenness Centrality, Clustering Coefficient, Average Shortest Path Length, Radiality, and Stress.

The matches were recorded with a digital camera (Sony Handycam DCR-SR210) used to capture the passing actions performed by the players, as well as the zone field where they took place. The camera was mounted on a tripod (Sony VCT-R6400) positioned at the centre of the fields, with an elevation of 6 and 20 meters from the field. The footage was transferred to a computer via USB and analysed with Windows Media Player (Microsoft Corporation, USA). All data were recorded in Microsoft Office Excel (Microsoft Corporation, USA) and subsequently exported to SPSS Statistics, version 32.0 (SPSS Inc., Chicago, USA), as well as to Cytoscape software (3.10.2).

Data analysis

A successful network connection was considered whenever the ball was passed from one player to another on the same team, reaching the intended player accurately and in control, without interference from the opponent, contributing to the continuity of the play and strategic advancement on the field. The following steps were followed: (i) the data were imported and reviewed to ensure consistency and accuracy; (ii) network metrics were calculated using specific formulas as described in the literature (Duch & Amaral, 2010; Yamamoto & Yokoyama, 2011; Passos et al., 2011; Clemente et al., 2016; Gonçalves et al., 2017).

The inter-observer agreement level for identifying passing relationships was (Kappa = 0.84). Reliability was assessed by the authors coding three randomly selected matches, with the data being compared among themselves.

Statistical analysis

The results are presented as means ± standard deviations (SD). The normality of the data was assessed using the Kolmogorov-Smirnov test, along with skewness and kurtosis coefficients, and through visual inspection of box plots, normal quantile-quantile (QQ) plots, and histograms. The dependent variables, including playing surfaces, players' tactical positions, and field zones, were analysed using a two-factor repeated measures analysis of variance (ANOVA).

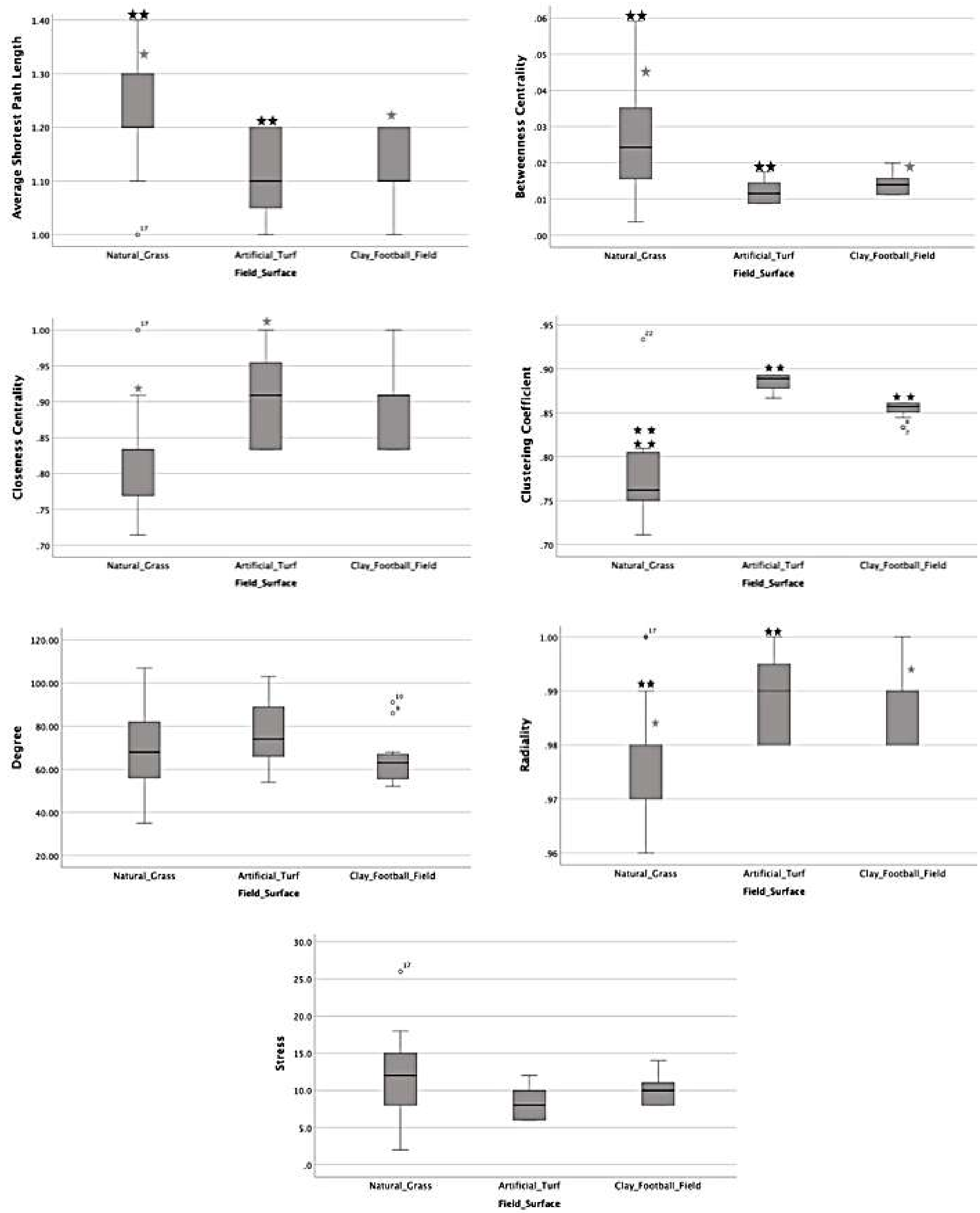
Effect sizes were reported as partial eta squared (η^2) obtained from the ANOVAs, following Cohen's guidelines (Cohen, 2013): (i) $0.01 \leq \eta^2 < 0.06$ – small effect; (ii) $0.06 \leq \eta^2 < 0.14$ – moderate effect; and (iii) $\eta^2 \geq 0.14$ – large effect. Significant main effects of each factor were followed up with Bonferroni-corrected post hoc multiple comparisons tests. All statistical analyses were conducted using SPSS Statistical Analysis software (SPSS Inc., Chicago, USA) version 32.0 for Windows. Significance was defined as $p \leq .05$, consistent with conventional thresholds for statistical significance.

RESULTS

The results are presented in terms of network metrics calculated for each field surface type. Figure 2 shows the main differences found in passing relationships established by players according to the field surface: (i) average shortest path length $F(2,052) = 6.099$; $p < .006$, $\eta^2 = 0.289$; (ii) betweenness centrality $F(2,001) = 7.294$; $p < .003$, $\eta^2 = 0.327$; (iii) closeness centrality $F(2,025) = 5.207$; $p < .011$, $\eta^2 = 0.258$; (iv) clustering coefficient $F(2,032) = 23.679$; $p < .001$, $\eta^2 = 0.612$; and (v) radiality $F(2,001) = 6.099$; $p < .006$, $\eta^2 = 0.289$.

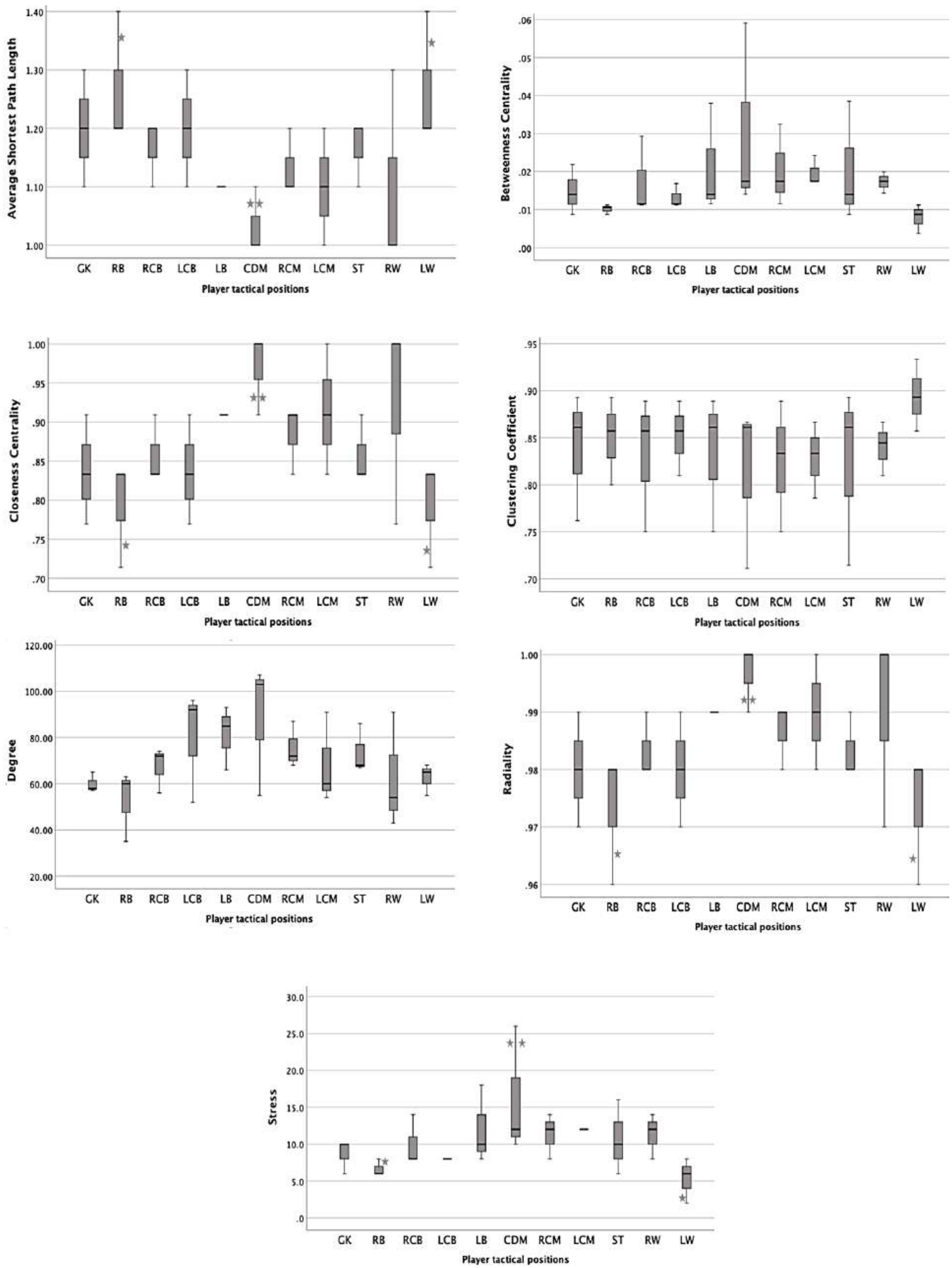
The results showed that artificial turf tends to exhibit higher values of Closeness Centrality and Radiality, reflecting greater fluidity in ball distribution. Natural grass presents a balance in the metrics, with moderate values in Degree, Closeness Centrality, and Clustering Coefficient, suggesting a more balanced tactical cohesion. Clay football fields show higher values of Stress and Betweenness Centrality, indicating a greater load on players in terms of transition and ball control. Figure 3 shows the main differences found in network metrics related to players' tactical positioning.

Closeness centrality varied significantly across tactical positions, $F(10.009) = 1.918$, $p < .05$, $\eta^2 = 0.466$. On artificial turf, attackers exhibited higher closeness centrality, reflecting a more effective penetration ability. In contrast, on clay football field, midfielders showed the highest closeness centrality, suggesting a need for more constant support during transitions. The analysis of passing networks (Figure 4) reveals that natural grass surfaces reflect a high density of connections, with many links between players, suggesting a playing style based on short and frequent passes, facilitating a fluid and dynamic game. Concomitantly, centrality on natural grass presents a strong central core, namely the connections of central midfielders and defenders, suggesting that they are key players in maintaining possession and distributing the ball.



*Note. Significant difference between conditions; *(p < .05) and **(p < .001).*

Figure 2. Metrics relating to passing relationships established by players depending on the pitch surface(mean ± SD).



*Note. Significant difference between conditions; *(p < .05) and **(p < .001).*

Figure 3. Metrics related to the tactical positioning of players (mean ± SD).

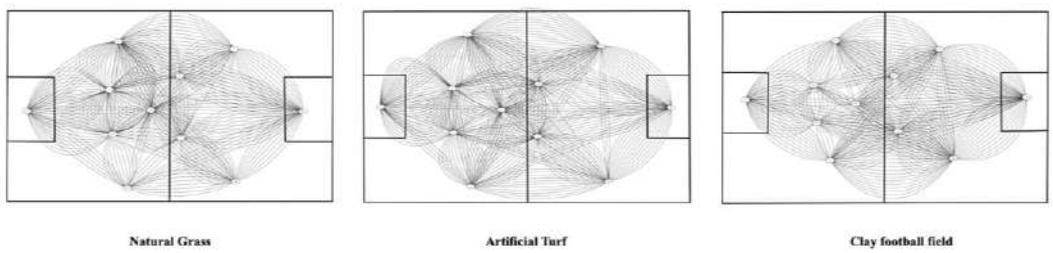
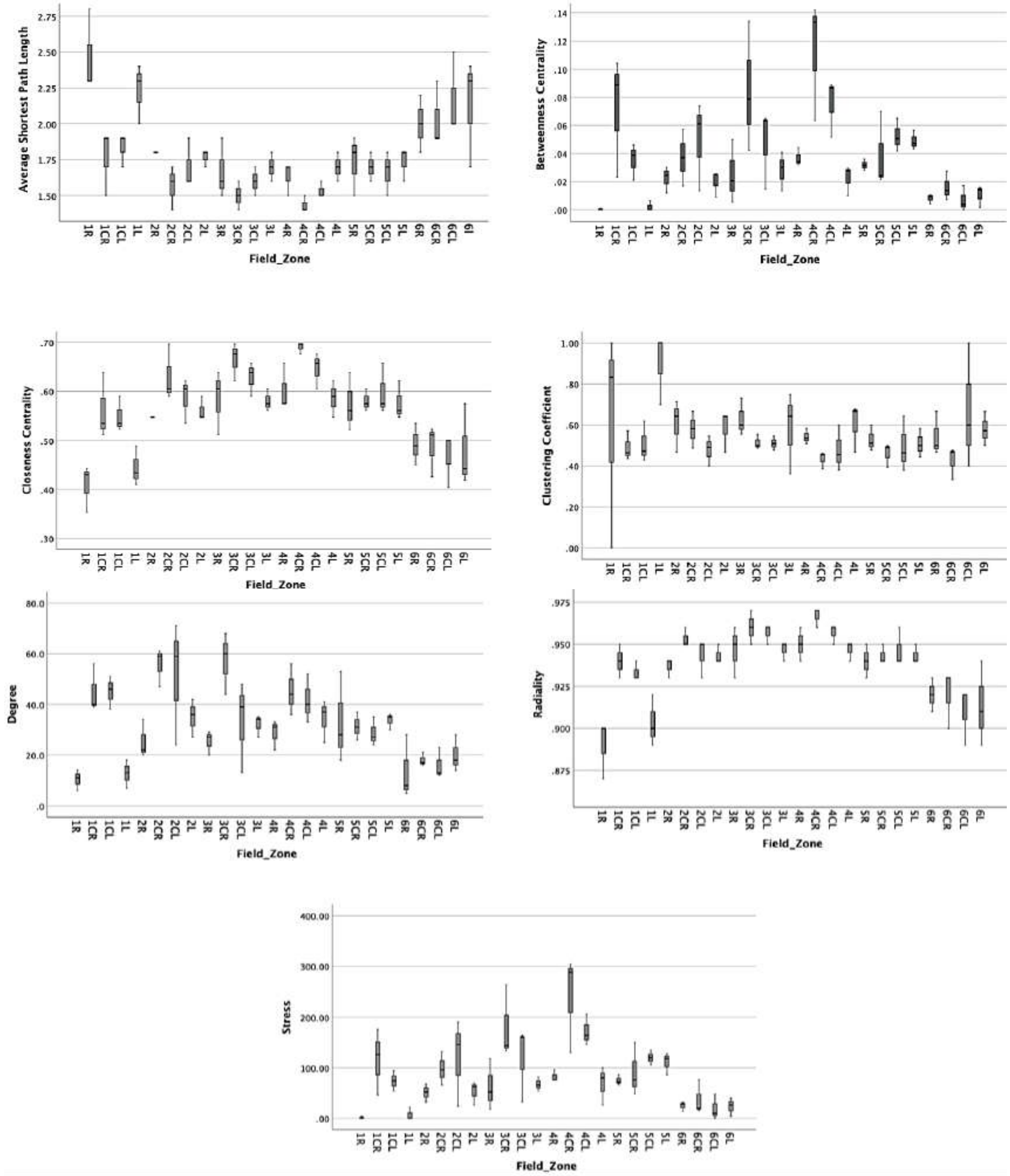


Figure 4. Passing networks established by players on different pitch surfaces.



*Notes. Significant difference between conditions; *(p < .05) and **(p < .001).*

Figure 5. Metrics relating to passing relationships established by players depending on the area of the pitch (mean ± SD).

Finally, on clay football field the density of connections shows a more dispersed arrangement in the midfield, suggesting that adapting to the surface may hinder quicker and more accurate passes. The centrality analysis reveals that players seem to have a more equitable involvement in the passing network with less reliance on specific players, suggesting that this surface is less predictable.

Figure 5 provides insights into how passing relationships vary across different zones of the field. Specifically, significant differences were found in: (i) average shortest path length $F(23.193) = 6.057$; $p < .001$, $\eta^2 = 0.744$; (ii) betweenness centrality $F(23.002) = 5.103$; $p < .001$, $\eta^2 = 0.710$; (iii) closeness centrality $F(23.015) = 6.835$; $p < .001$, $\eta^2 = 0.766$; (iv) degree $F(23.592) = 5.298$; $p < .001$, $\eta^2 = 0.717$; (v) radiality $F(23.001) = 8.366$; $p < .001$, $\eta^2 = 0.800$; and (vi) stress $F(23.073) = 5.302$; $p < .001$, $\eta^2 = 0.718$.

Figure 6 shows that the density and complexity of lines vary, suggesting different movement patterns depending on the surface type. Natural grass shows more concentrated movement in the centre.

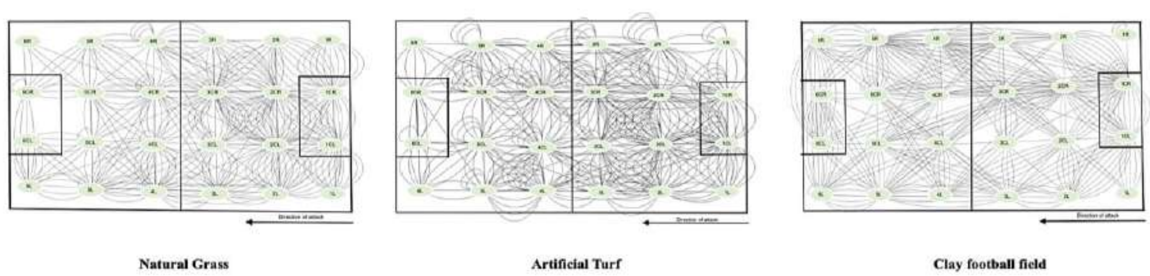


Figure 6. Passing networks established by players in different areas and surfaces of the field.

On the other hand, artificial turf shows a high density of lines across the entire field, suggesting a more balanced distribution across all zones of the field. Regarding the clay football field, although it concentrates the main activity in the central area of the field, it also shows a tendency for longer connections between different zones, suggesting a more direct style of play.

DISCUSSION

This study aimed to investigate how different playing surfaces (artificial turf, natural grass, and clay football field) influence the structure and functionality of passing networks in football. Specifically, the study intended to: (i) Assess how player centrality in passing networks varies according to the playing surface, the tactical positioning of players, and the zone of the field; (ii) Measure the tactical cohesion of teams on different playing surfaces; (iii) Determine the efficiency of passing networks in terms of speed and accuracy; and (iv) Identify and compare the movement patterns and strategies adopted by teams on different playing surfaces, observing differences in game dynamics and passing execution. The study results provide a detailed overview of the game dynamics in youth football on different playing surfaces, using passing network analysis. This discussion will analyse the findings based on the calculated metrics, player tactical positions, and zones of the field, relating them to the existing literature.

Network metrics by surface type

The analysis of network metrics revealed significant variations among natural grass, artificial turf, and clay football field. On natural grass surfaces, we observed a higher Clustering Coefficient and greater Betweenness Centrality, indicating greater cohesion and collaboration among players. This result suggests that natural grass, due to its more uniform surface, allows for a more integrated and collaborative game, facilitating frequent interactions between players. The literature supports this observation, as highlighted by Andersson et al. (2008), who found greater fluidity and efficiency in plays on natural grass due to the predictability of the surface.

On artificial turf surfaces, metrics indicated a faster and more direct style of play, with a slight increase in Closeness Centrality. This suggests that players tend to adopt a playing style that takes advantage of the lower rolling resistance of the ball, enabling rapid transitions. This characteristic is corroborated by studies such as Impellizeri et al. (2009), who observed an increase in the speed of play on artificial surfaces.

Conversely, clay football fields exhibited lower network efficiency, with a lower Clustering Coefficient and a less centralized ball distribution. This surface suggests significant challenges for maintaining a fluid style of play, reflecting the findings of Mendiguchia and Buchheit (2016), who pointed to difficulties in controlling and accurately passing the ball on irregular terrain.

Metrics related to the tactical positioning of players

Results also indicated tactical differences associated with each surface type. On natural grass, players exhibited greater positional balance, allowing for a uniform distribution of interactions and mutual support, favouring a more structured tactical strategy. This balanced positioning can maximize attacking and defensive opportunities, as discussed by Fernandez-Navarro et al. (2018), who highlight the importance of a cohesive team structure for tactical success.

On artificial turf surfaces, the analysis suggests an increase in transition and counter-attack plays, with players occupying more advanced and aggressive positions. This behaviour may be a response to the surface's ability to support rapid movements, as observed by Di Salvo et al. (2007), who suggest that artificial surfaces encourage a more direct style of play.

On the other hand, clay football field reflected a more defensive and compact positioning, possibly as an adaptation to the difficulty of executing accurate passes. This finding highlights the need to adjust tactical strategies to mitigate the challenges presented by the surface, aligning with the observations of Goto and Okano (2020) who discuss tactical adaptation as a necessary response to adverse playing conditions.

Metrics according to the zone of the field

The analysis of field zones revealed that natural grass facilitated a more balanced and effective use of all zones, with players exhibiting fluid movement between defensive, midfield, and attacking zones. This flexibility is critical for maintaining control of the game and creating scoring opportunities, as discussed by Clemente and Serrani (2016), who highlight the importance of the ability to transition between zones in football.

In contrast, the artificial turf surface demonstrated a greater focus on attacking zones, reflecting an offensive-oriented strategy. This emphasis on advanced zones is consistent with the research of Modric et al. (2023), who associate artificial turf with an increase in attacking opportunities due to the faster pace of the game.

Finally, the clay football field reflected a higher concentration of play in the defensive and midfield zones, suggesting a more cautious approach to defensive positioning. On the other hand, a more aggressive approach to offensive positioning seems visible, probably with the purpose of pressing higher to take advantage of the unevenness of the ground and provoke errors in the opponent, recovering the ball in high areas of the field and quickly approaching the goal in favourable conditions. This is in line with the theory that irregular surfaces limit the effectiveness of game indicators (Andersson et al., 2008).

CONCLUSIONS

This study concludes that the playing surface has a significant impact on the dynamics of the game and the tactical effectiveness of youth soccer teams. Natural grass surfaces provide better conditions for tactical cohesion and passing accuracy, allowing for a more collaborative and structured game. In contrast, clay football field presents substantial challenges for maintaining a fluid playing strategy, resulting in a more defensive and cautious approach. Artificial turf encourages a faster and more direct game, favouring attacking strategies. These findings underscore the importance of adjusting tactical and training strategies according to the field conditions to maximize performance. The study also highlights the value of pass network analysis as a powerful tool for understanding team dynamics and the impact of playing surfaces. Future studies should investigate adaptive training interventions and explore the longitudinal effect of surfaces on the skill development of young players. In summary, understanding the influences of playing surfaces can inform strategic decisions and optimize performance in youth soccer.

Limitations and future research

As limitations of this study include its restriction to a specific age group and the lack of control over external variables such as weather conditions. Future research could explore more diverse samples and consider the use of advanced technology to capture more precise data on the impact of playing surfaces on the game. New investigations could also explore specific training interventions to help players better adapt to the challenging conditions of surfaces like clay and longitudinally analyse how different surfaces affect skill development over time.

AUTHOR CONTRIBUTIONS

Ângelo Brito: Responsible for the conceptualization, study design, data analysis, interpretation of results, and manuscript drafting. Luís Freitas: Contributed to data collection and preprocessing.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ACKNOWLEDGEMENTS

We thank to all the players and managers of the soccer teams for their collaboration.

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ORIGINAL ARTICLE

Loaded hip thrust-based PAP protocol effect on 20 meters sprint performance

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ABSTRACT

Background and Study Aim. This study aimed to investigate the effects of post-activation strengthening protocol (PAP) based on barbell hip thrust movements with different rest intervals on subsequent sprint performance. Material and Methods. Nine physical education and sports students (age 19.5 ± 0.2 years; height 180.3 ± 5.2 cm; body mass 81.2 ± 6.9 kg) participated in the study. 1RM of the barbell hip thrust movements of the athletes was taken and 85% of the movement was calculated (85 PAP). The athletes performed three different protocols after the dynamic warm up. The first protocol was 85PAP + 15 s rest interval, the second protocol consisted of 85PAP + 4 min rest interval; and the other protocol was 85PAP + 8 min. rest interval. Each protocol was followed by a 20-m sprint. Results. After the 85PAP protocol, there was a decrease in the sprint time after 15 s, 4 and 8 minutes ($p < .05$). Conclusions. When the waiting time increased, the sprint performance improved. This study demonstrated that intensive BHT exercise could increase the PAP effect. It was also found that the effect of the intensive BHT could vary according to the strength level of the individual.

Keywords: Performance analysis, Hip thrust, Strength, Pap, Neuromuscular abilities, Sprint.

Cite this article as:
Vurmaz, M. O., Kösemen, S. D., Akdeniz, H., Alpay, D. A., Töre, O. A., & Bingül, B. M. (2025). Loaded hip thrust-based PAP protocol effect on 20 meters sprint performance. *Journal of Human Sport and Exercise, 20*(2), 459-469. https://doi.org/10.55860/azqt2512

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Submitted for publication November 26, 2024.
Accepted for publication January 10, 2025.
Published February 10, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/azqt2512

INTRODUCTION

Various forms of warm-up exist for practice, training, and competition activities of athletes. The traditional warm-up paradigm involves a brief period of low intensity aerobic-type activity, followed by static stretching and activity-specific movements (Schıllıng & Stone, 2000). The previous studies that supported these methods partly and as a whole concluded that they were equivocal, suggesting both positive and negative effects (Schıllıng and Stone, 2000). Since the physiological requirements of activities differ, the type of warm-up should also be specific to the requirements of the task. The overall intention of the warm-up should be to maximize performance acutely and reduce risk of injury in the given sport (Schıllıng and Stone, 2000; Guillich and Schmidtbleicher, 1996).

Heavy resistance training is a component in the long-term preparation of athletes for competition. The primary purpose of chronic heavy resistance training for athletes is typically to increase muscle force production, and subsequently velocity and power expression. Heavy resistance training, when performed in a maximally accelerative pattern, results in long-term improvement in measures of power and explosive force (Moss et al., 1997). Despite the research focusing on the long-term effects of heavy resistance training, the current understanding of the acute effects is less than comprehensive. On an acute level, it is clear that excessive volume and load may result in fatigue (Hakkınen, 1993). However, scenarios exist in which heavy weight training may enhance performance immediately afterwards (Hamada et al., 2000; Smith et al., 2001).

Post activation potentiation refers to a "*phenomenon whereby muscular performance is enhanced acutely after an activity executed at a relatively higher intensity*" (Lowery et al., 2012). Enhanced rate of force development and muscular power augment explosive muscle actions such as jumping (Kilduff et al., 2007; Kilduff et al., 2008). Suggested mechanisms for PAP are the phosphorylation of myosin regulatory light chains, subsequently increasing myofibrillar sensitivity to Ca2 + secretion from the sarcoplasmic reticulum, and increased recruitment of higher order motor units (Gullıch and Schmıdtbleıcher, 1996; Hamanda et al., 2003; Hodgson et al., 2005; Osteras et al., 2002). This acute enhancement of muscular power has been suggested as the premise upon which complex training is based (Ebben, 2002). Through this enhancement of muscular power, complex training is expected to produce superior chronic exercise adaptation in comparison to traditional strength and power training combinations (Ebben, 2002; Gullıch and Schmıdtbleıcher, 1996). Acute increases in performance can be substantially affected by the balance between PAP mechanisms and fatigue (Chatzopoulos et al., 2007; Jones and Lees, 2003). These "*opposing effects*" have usually produced inconsistent findings and unclear training guidelines (Lowery et al., 2012; Mola et al., 2014; Sale, 2002). Moreover, it appears that this balance may be altered by several factors, such as training experience, length of the rest period prior to subsequent exercise as well as the volume and intensity of conditioning activity (Wilson et al., 2013).

Accordingly, many studies have been designed to determine the optimal PAP strategy to induce positive short-term effects in trained subjects (Gourgoulis et al., 2003; Hanson et al., 2007; Jones and Lees, 2003; Young et al., 1998). In order the PAP to be effective, a recovery interval of 4 to 11 min is required (Seitz & Haff, 2016; Wilson et al., 2013; Kilduff et al., 2008). This could stem from the hypothetical relationship between PAP and fatigue (Tillin and Bishop, 2009). At the completion of the conditioning activity, both potentiation effects and fatigue are present, but closer to the conditioning activity, due to acute biochemical and mechanical alterations, muscular fatigue overcomes the potentiation effects leading to reduced performance (Benister et al., 1999). DelloIacono and Seitz (Dello and Seitz, 2018), recently proposed a novel approach to enhance PAP effects: by using the optimum power load (Loturco et al., 2015) in the conditioning activity, less fatigue should be accumulated, allowing for greater potentiation effects in the subsequent activities (Tillin and Bishop, 2009; Benister et al., 1999). This logic is based on the fact that optimum power loads are lighter compared to the relatively heavier loads (i.e., >85% 1RM) commonly used to elicit a PAP effect, and are thus expected to be less fatiguing while everything else is equal. It should be noted that optimum power could be defined as the mean propulsive power output calculated from the portion of area under the power-time curve, during which the acceleration of the upward motion is greater than gravity (i.e., a ≥ 9.81 m • s-2) (Loturco et al., 2015).

To test this hypothesis, Dellolacono and Seitz (Dello & Seitz, 2018) compared the effects of two PAP protocols on sprint performances of elite male handball players using either 85% of 1RM, or a load enabling optimum power development, with the exercise modality being the barbell hip thrust. Greater impairments in 5 m and 10 m sprint performances were observed following the 85% of 1RM protocol immediately after the conditioning activity, and greater improvements in 5 m, 10 m and 20 m sprint distances after 4 min and 8 min following the optimum power protocol.

METHOD

Study design

The sprints were measured using electronic timing gates positioned at the start line, 10 and 15 meters from the start line, and at 0.5 meters height from the ground. All athletes initiated the sprint, in their own time, from a semi-crouched position with the front foot 20cm from the start line. The athletes received verbal encouragement to sprint at maximal effort. Following the baseline assessment, the athletes performed experimental PAP protocol, and then were reassessed for a single 20m sprint with maximal effort at 15s, 4min, and 8min. The 20 m sprint performances performed in different protocols were recorded and analyzed.The participants performed either three sets of six repetitions of 85PAP, matched according to the calculation described above. These conditioning protocols were used since they were commonly included as part of weekly conditioning programs. The rest period between sets was 2min. This rest period was determined because the BHT was sufficient to prevent execution failure at the 85% PAP protocol stage. 85% PAP Protocol were performed at a self-chosen pace, with one researcher and one coach supervising all exercises and providing appropriate motivation.

Data collection

Nine male (age 19.5 ± 0.2 years; height 180.3 ± 5.2 cm; body mass 81.2 ± 6.9 kg) students from Kocaeli University Sports Faculty volunteered to participate in the study. The athletes had at least five years of practice as four days a week in different branches, which were jumping, sprint and resistance exercises. Written informed consent was obtained from the athletes after they received an oral explanation of the purpose, benefits, and potential risks of the study. All procedures were conducted in accordance with the Helsinki Declaration.

Research design

1RM of the barbell hip thrust movements of the athletes was taken and 85% of the movement was calculated (85 PAP). Athletes first performed a 15-min general warm-up consisting of various dynamic mobilization exercises for the lower body musculature. After the warmup, three different protocols were performed on same days (Fig. 1). The first protocol was 85PAP + 15 s rest interval, the second protocol consisted of 85PAP + 4 min rest interval; and the other protocol was 85PAP + 8 min. rest interval. Following each protocol, 20-meter sprint time was taken with photocell. It was used to compare the effects of 85% 1Rm (85PAP) PAP protocols on subsequent performance. First of all, BHT 1 RM values were calculated. Anthropometric measurements of body and body masses were made on the same day after one week, and sprint performances of 85% PAP were calculated. Accordingly, the BHT exercise was performed by having the upper back of the participant rest on a bench. Feet of the participants were slightly wider than shoulder-width apart, with the toes on the hips of the participant. The participants were instructed to thrust the barbell upwards while maintaining a neutral spine and pelvis. (Table 1).

Table 1. PAP Protocol Practice %85 PAP (BHT) + Sprint Protocol.

P1	Six repetition %85PAP (BHT) + 15 sec. Recovery duration 20 m. sprint
P2	Six repetition %85PAP (BHT) + 4 min. Recovery duration 20 m. sprint
P3	Six repetition %85PAP (BHT) + 8 min. Recovery duration 20 m. sprint

Between each protocol, the heart rates of the athletes were checked for recovery. The athletes with 110HR/Min were deemed ready for the next protocol

20-m Sprint Test

The sprints were measured using electronic timing gates (Photocell, 0.001 s accuracy, Bolzano, Italy) positioned at the start line and 20 m from the start line. All athletes initiated the sprint in their own time, from a semi-crouched position with the front foot 20 cm from the start line. After each BHT exercise, the athletes had a sprint performance of 20 m after different recovery durations (15 sec, 4 min, 8 min). The athletes received verbal encouragement to sprint at maximal effort.

Data analysis

The statistical analysis and descriptive statistics of the data obtained were made with the Statistical Package for the Social Sciences Statistics 25.0 (IBM SPSS Corp., Armonk, NY, ABD) package program. In statistical analysis of data Friedman test was used and then analysed using Wilcoxon binary comparison test.

RESULTS

The sprint time data of the three protocols are presented in Table 2. The sprint times, which were measured according to the 85 % PAP protocol, a comparison was made between the 20 m sprint performances after recovery durations of 15 seconds, 4 minutes and 8 minutes. There were significant differences between the sprint times in the 20 m sprint performances, which were performed after different recovery durations following 85% PAP (Figure 1). Looking at the 20 m sprint times following the 85% PAP protocol, a significant difference was found between the sprint performances after 4-8 minutes of recovery duration and the sprint performances after 15 seconds of recovery duration (p = .012; .011). When the sprint performances after 4 and 8 minutes of recovery duration were compared, the best sprint performance was observed in sprint time after 8 minutes of recovery duration (p = .033).

Table 2. Sprint times (mean 90%) at baseline and different times points after the 85% 1RM hip thrust, corresponding effects sizes and qualitative inferences.

Protocol	N	Variable	15 s Rest.	4 min Rest.	8 min Rest.	Qualitative Inference		
						15s	4 min	8 min
85% PAP	9	20 meters	3.19	3.09	3.05	Most likely trivial	Very likely beneficial	Very likely beneficial

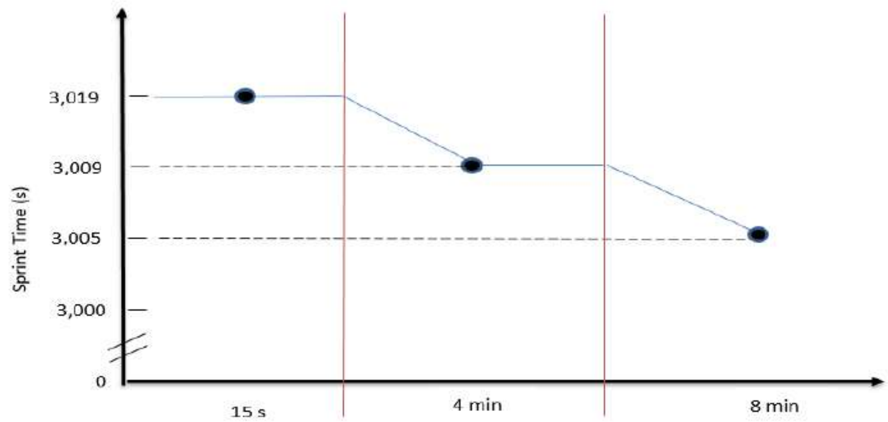

Figure 1. Plot of the time course effects following the% 85PAP protocol on 20-meter sprint performance. There was a statistical significance in the means compared to baseline following the 85PAP protocol; data were presented as means ± SD.

Table 3. Descriptive statistics results of the 20-meter sprint performances with 85% PAP protocol.

Protocol	n	Mean	SD	Min.	Max.
PAP15s Rest.	9	3.19	.13	2.90	3.36
PAP4m Rest.	9	3.09	.20	2.70	3.29
PAP8m Rest.	9	3.05	.21	2.65	3.25

Note. SD, standard deviation; min, minimum; max, maximum; n, number of people; PAP15s Rest, post activation potentiation after 15 seconds rest; PAP4m Rest, post activation potentiation after 4 minutes rest; PAP8m Rest, , post activation potentiation after 8 minutes rest.

Table 4. Comparison of trial times.

PAP4m - PAP15s	PAP8m - PAP15s	PAP4m - PAP8m
-2.521b	-2.547b	-2.136b
.012	.011	.033

Note. PAP4m - PAP15s, Post activation potential Difference between 4 minutes and 15 seconds; PAP8m - PAP15s, Post activation potential Difference between 8 minutes and 15 seconds; PAP4m - PAP8m Post activation potential Difference between 4 minutes and 8 minutes. Note: After 15 seconds, 4 minutes and 8 minutes of rest, the sprint performance showed a significant difference in resting for all durations (p < .05).

DISCUSSION

Researchers, who examined the mechanism behind PAP following complex strength training, established a relationship between post-activation potentiation and improvements in speed and explosive strength of athletes. Most of the papers have confirmed the effectiveness of PAP in eliciting performance in tasks requiring speed, jumping ability and agility in soccer players (Pajerska et al., 2020).

In a study by (Dello et al., 2018) carried out with 18 male handball players, a significant difference was observed in sprint performances of 10 meters and 15 meters after 4 minutes and 8 minutes rest after loading with barbell hip thrust with 85% 1RM. This study showed that both moderate and intensive BHT exercises could induce a PAP response; however the effects could differ according to the recovery following the potentiating stimulus and the strength level of the individual.

In a study by (Dello and Seitz, 2018) carried out with 18 football players, a significant difference was observed in sprint performances of 5 meters, 10 meters and 20 meters after 15 seconds, 4 minutes and 8 minutes rest following the loading with barbell hip thrust with 85% 1RM ($p < .05$). Barbell Back Squat is a highly effective training stimulus that enhances the features of the lower body such as strength, speed, and sprint. Athletic performance is considered to be the key component in many sports branches. Barbell Hip Thrust Exercise makes use of a similar muscular system and is a popular exercise among practitioners. However, there are very few academic studies.

In a study by (Millar et al., 2020), a resistance training program was developed consisting of barbell hip thrust and back squat exercises to evaluate the physical performance of female footballers. As a result of the study, it was determined that the barbell hip thrust and back squat movements were both effective stimulants for this sports branch.

In a study performed by (Rahimi, 2007), 12 male elite league players was administered 60%, 70% and 85% squat with 1RM followed by a 40-meter sprint and 4-minute rest PAP protocol. Following the PAP protocol, a significant difference was observed in loads with 70% and 85% power followed by 4 minutes of rest. In our study, declines were observed in all sprint times after all intervals following the 85% PAP protocol.

Similarly, in a study conducted by (Wyland et al., 2015), on 20 male individuals who were engaged in recreational weight exercise, the 10-meter sprint performance was observed after 1 minute, 2 minutes, 3 minutes and 4 minutes of rest following the back squat movement with 1RM 85% loading, and a more decrease was observed in the sprint times in the 10-meter sprint performance after 4 minutes of rest when compared to other minutes of rest ($p < .05$).

In the study conducted by (Chatzopoulos et al., 2007) with 15 male athletes competing in different branches of amateur leagues, no significant difference was found 30-meter sprint performances after 3-minute and 5-minute rests following the back squat exercise with the 1RM 90% PAP protocol; however, significant differences were observed in the 0-10 meter and 0-30 meter sprint tests followed by a 5-minute rest.

In a study conducted by (Bevan et al., 2010), with 16 male rugby players, 5 meter and 10 meter sprint performances after back squat exercise with 1RM 90% PAP protocol followed by 4, 8, 12 and 16 minutes of rest, no difference was observed in the 5 and 10 meter sprint performances; however, individual differences were observed between the best sprint times in the 5 meter and 10 meter sprint tests.

In a study conducted by (Loturco et al., 2018), with elite athletes, the relationship between vertical and horizontal strength exercises with sprint performances of 10, 20, 40, 60, 100 and 150 meters was analysed and it was observed that particularly the barbell hip thrust movement demonstrated a high correlation in the 10-meter acceleration phase.

In our study, when the sprint values of the participants were analysed individually after the barbell hip thrust movement, it was observed that the sprint scores decreased after 15s, 4 and 8 minutes of rest in the 20-meter acceleration phase. Performance improved as the resting time increased.

In the study carried out by (Till & Cooke, 2009), on male academy football players, the effect of post activation potential on the sprint performance and vertical jump length of male academy football players was analysed. According to the 10-meter and 20-meter vertical jump performances deadlift exercise with 80% 1RM loading followed by 4 minutes of rest, a significant difference was observed in the 20-meter sprint performance compared to the 10-meter sprint performance. In terms of the vertical jump performance, a greater performance outcome was observed when compared to the sprint performance of 10 meters and 20 meters.

In a study carried out by (Contreras et al., 2017), on adolescent rugby players, a comparison was made between the groups in 10-meter and 20-meter sprint performances of back squat and barbell hip thrust trainings following a 6-week back squat and barbell hip thrust exercise protocol. A decrease was observed in the sprint scores obtained in the 10-meter and 20-meter sprint tests by the group, which performed the barbell hip thrust exercise, when compared to the back squat group.

In our study, the acute effect was observed after resting for 15 seconds, 4 minutes and 8 minutes following the barbell hip thrust workouts, and decreases were observed in 20-meter sprint performances. Due to the high level of muscle activation of barbell hip thrust workouts in the hip region, acute and chronic decreases were observed in sprint performances of 0-10, 0-20, 0-30 meters after the workouts. Although this effect was a chronic effect; this result was supported in many resources indicating the fact that the barbell hip thrust workouts caused in more muscle activation in the hip region compared to the back squat training.

In another study that was parallel to our study, (Orjalo, 2019) investigated the effect of Barbell Hip Thrust movement on direction change performance with a total of 40 people who were doing recreational sports in groups of female and male. After the PAP protocol with 85% RM, the 505 COD test was administered. Before the 505 COD test was administered, the 505 COD test performances of the participants were evaluated after 4, 8, 12 and 16 minutes. There was an increase in the 505 COD test performances after all the resting periods following the PAP protocol.

This result stems from the improvement in the movement patterns in the vertical direction after the strength workouts that were performed in the vertical direction biomechanically. In the strength workouts performed in the horizontal direction, the movement patterns in the horizontal direction improved. In the studies carried out, a parallelism is observed on the sprint performance with the force output in the horizontal direction. This study showed that intensive BHT exercise could increase the PAP effect. It was also found that the effect of the intensive BHT could vary according to the strength level of the individual. As the previous studies demonstrated, the activation of the muscles in the gluteal region was high in BHT exercises; and the activation of the muscles in the hip region was quite high in the exercises such as sprint. Another conclusion from this study was that the choice of movement for regions with high muscle activations during the movement pattern could provide a positive transfer of movement to the performance. At the same time, the exercises performed in the horizontal direction could have positive contributions to the exercises such as sprint, which were performed in the horizontal direction, due to the fact that both exercises were performed in the same movement pattern. Decreases could be observed in the sprint times as the resting periods are increased; this could be associated with the regeneration of tap creatine phosphate located in the muscle.

CONCLUSION

All variables initially produced highly reliable data. Comparing 20-meter sprint performances after 15 seconds, 4-minute and 8-minute rests by making 85% PAP protocol, significant differences were detected in the 20-meter sprint performances of the athletes (Table 1). Significant differences following the PAP protocols were also evident, as supported by large effects and qualitative outcomes (Table 4). After performing 85 PAP, beneficial and possible positive effects were observed. In the light of this information, improvements in 20m performances were noticed at 4 and 8 minutes time points (Table 2).

Looking at the 20-meter sprint times obtained after the 85% PAP protocol, a positive difference was observed in the sprint performances performed after 4 and 8 minutes of rest compared to the sprint performance performed after 15 seconds of rest (p < .05). When 4 and 8 minute sprint performances were compared, a positive difference was observed in the sprint performance performed after 8 minutes rest with the 85% PAP protocol compared to the 4 minute sprint performance (p < .05) (Table 4).As a result, a greater increase and development was observed in the 8-minute 85% PAP protocol compared to the 15-minute and 4-minute 85% PAP protocol (Table 2).

AUTHOR CONTRIBUTIONS

These should be presented as follows: Initials (Vurmaz, M. O.) and Initials (Bingül, Meriç, B) were used to design the study. Initials (Vurmaz, M. O.) performed the research. Initials (Akdeniz,H) provided help and advice on research and discussion. Initials (Kösemen, D, S) analysed the data. Initials Vurmaz, M, O., Kösemen S. D., Akdeniz, H., Alpay, D. A., Bingül, Meriç, B, S., and Töre, Ağca, Ö) wrote the manuscript. All authors contributed to the editorial changes in the manuscript. All authors have read and approved the final version of the manuscript.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

AVAILABILITY OF DATA AND MATERIALS

The data presented in this study are available on reasonable request from the corresponding author.

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ORIGINAL ARTICLE

Is the acid-base status at rest related to endurance performance in 10-km runners?

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ABSTRACT

This study aimed to compare acid-base parameters between elite (ER) and amateur (AR) runners at rest and to explore potential correlations with 10-km running. Each participant completed a 10-km time trial on a 400-meter track, underwent an incremental exercise test in laboratory conditions, and provided a resting blood sample for analysis. Capillary blood sample were collected from the fingertip at rest. Measurements included pH, partial pressure of dioxide carbon (pCO_2), haematocrit (Hct), haemoglobin (Hb) and lactate (Lac^-), sodium (Na^+), potassium (K^+), chloride (Cl^-) and bicarbonate (HCO_{3-}) ions. Base excess (BE) and strong ions difference (SID) was calculated. No significant differences were observed between ER and AR for Hb, K^+, Lac^-, and pH ($p > .05$). ER exhibited significantly higher values for HCO_{3-} (ER = 28.5 ± 1.8; AR = 25.7 ± 1.7 $mmol{\cdot}l^{-1}$), Cl^- (ER = 104.4 ± 3.83; AR = 100.1 ± 3.89 $mmol{\cdot}l^{-1}$), BE (ER = 5.6 ± 1.6; AR = 3.21 ± 1.43 $mmol{\cdot}l^{-1}$) and pCO_2 (ER = 36.9 ± 3.7; AR = 33.9 ± 2.9 mmHg; $p < .05$). SID (ER = 49.0 ± 5.70; AR = 41.3 ± 5.23 $mmol{\cdot}l^{-1}$; $p < .05$) and Na^+ (ER = 140.0 ± 4.1; AR = 143.5 ± 3.3$mmol{\cdot}l^{-1}$; $p < .05$) were significantly lower in ER. Strong correlations were found between HCO_{3-}, SID, ventilatory threshold parameters and 10-km performance ($p < .05$). These findings suggest that resting acid-base status can be a useful indicator of 10-km performance and can assist in monitoring training-induced adaptations.
Keywords: Sport medicine, Acid-base profile, Running, Athletes.

Cite this article as:
Lourenço, T.F., Nunes, L. A. S., Artioli, G. G., Martins, L. E. B., Brenzikofer, R., & de Macedo, D. V. (2025). Is the acid-base status at rest related to endurance performance in 10-km runners?. *Journal of Human Sport and Exercise, 20*(2), 470-478. https://doi.org/10.55860/zw2eg158

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Submitted for publication October 14, 2024.
Accepted for publication December 08, 2024.
Published February 10, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/zw2eg158

INTRODUCTION

Endurance performance is closely associated with maximal aerobic capacity (i.e., maximal oxygen uptake - VO_{2max}), anaerobic capacity, and running economy (Joyner et al., 2008). Recently, the concept of critical power/speed (CS) has emerged an additional determinant of endurance performance. This concept facilitates the prediction of exercise tolerance by identifying the critical power (CP) and the work or distance (W' or D') achievable above CP. The CS model characterizes the transition between heavy and severe exercise intensity domains, distinguishing between sustainable and unsustainable speeds over a given distance while maintaining in a physiological steady state (i.e. stable pulmonary VO_2, blood lactate levels, muscle [phosphocreatine] and pH, muscle O_2 saturation) (Jones et al., 2019; Poole et al., 2016).

Under laboratory conditions, one commonly used method to identify this domain transition involves analysing expired gases and the identification of the second ventilatory, also known as threshold or respiratory compensation point (RCP). The RCP has been associated with the total extra- and intra-muscular buffering capacity (Bhambhani et al., 2007; Wasserman et al., 2011) indicating that intensities above RCP lead to a failure to maintain pH levels, resulting in rapid acidosis. Our previous research (Lourenço et al., 2019a) demonstrated a strong correlation between 10-km performance and the running speed at the RCP (sRCP) ($r = 0.96$). Moreover, we observed that both amateur and elite runners select a running pace very close to sRCP during 10-km race.

Blood bicarbonate (HCO_3^-) is a crucial chemical buffer, playing a pivotal role in maintaining blood pH during exercise. An increase in resting HCO_3^- concentration has been shown to enhance buffering capacity. Acute and chronic sodium bicarbonate supplementation has been associated with elevated resting HCO_3^- levels, prolonging time to exhaustion and delaying the onset of acidosis during high-intensity tasks (Carr et al., 2011; Hadzic et al., 2019). However, no studies have specifically compared endogenous blood HCO_3^- levels at rest among runners and their correlation with competitive 10-km performance.

Levels of HCO_3^- are influenced by the partial pressure of carbon dioxide (CO_2) and haemoglobin (Hb) (Geers et al., 2000), both of which are affected by mitochondrial activity and red blood cells concentration - key adaptations induced by endurance training (Egan et al., 2013; Montero et al., 2017; Ucía et al., 2000). Therefore, resting HCO_3^- levels may reveal significant training-induced adaptations.

In addition to HCO_3^-, several other factors such as non-bicarbonate buffers, base excess (BE) and strong ions difference (SID) contribute to quantifying metabolic components related to blood pH control (Kellum, 2005). BE represents the amount of acid or base required to restore pH to 7.40, whilst SID is calculated as the difference between concentrations of strong cations and strong anions ($SID = [Na^+ + K^+] - [Cl^- + Lactate^-]$) affecting pH based on the principles of electroneutrality and mass conservation (Stewart, 1983).

Although BE has been shown to decrease during incremental exercise in marathon runners (Zoladz et al., 1993), it is currently unclear how BE is related to running performance. Considering the relevance of acid-base balance to endurance performance and the significant contribution of BE and SID to blood pH regulation, we hypothesized that resting BE and SID are associated with endurance running performance. This study aims to compare the acid-base profiles of elite and amateur runners at rest and explore their relationships with 10-km running performance.

MATERIALS AND METHODS

Experimental design

Initially, both professional and amateur 10-km runners individually performed a 10-km time trial on a 400-m outdoor track, with their time to complete the distance being recorded. Two days later, they visit the laboratory to collect blood samples at rest and underwent a maximal incremental running test to determine VO_{2max} and the running speed at the gas exchange thresholds.

Participants

Twenty-six amateur runners (AR; age:35 ± 6 years, body mass: 69.0 ± 10.1 kg, stature: 174 ± 0.1 cm) and nineteen elite runners (ER; age: 26 ± 6 years, body mass: 67.9 ± 8.7 kg, stature: 174 ± 0.1 cm) participated in the study. The ER were ranked among the top ten national ranking of 5-km and 10-km and were actively competing in national and international events at the time of the study. All athletes refrained from exercise for at least 48h before the tests and were instructed to maintain their usual diets for three days prior to the study. Informed consent was obtained from all participants in accordance with the guidelines of the Ethical Committee of University Research (nº 523/2010).

Procedures

Test 1: 10-km running trial

A 10-15-minute warm-up period preceded the test, which commenced at 9 A.M.. Participants were allowed to hydrate *ad libitum* during the trial. Each subject was verbally encouraged to exert maximal effort and was not permitted to use any time devices. The run took place on an official 400-m track, with lap times recorded to calculate average running speed and total time test, thereby determining the average speed over the 10-km distance (s10km).

Test 2. Blood analysis at rest

After fifteen minutes rest time (seated) capillary blood samples were collected from the fingertip using disposable lancets (Accu-Chek SoftClix®, Roche®) and heparinized glass micro-haematocrit capillary tubes (Clinitubes®, Radiometer Copenhagen®). Blood pH, carbonic dioxide partial pressure (pCO_2), haematocrit (Hct), Hb and blood lactate (Lac^-) were immediately analysed using the Stat Profile®-pHOx®PlusL blood gas analyser (Nova Biomedical®, MA, USA). Equipment calibration was performed immediately before and at regular intervals during the experiment as per the manufacturer's instructions. Coefficients of analytical variation (CVA) are showed in Table 2.

Sodium (Na^+), potassium (K^+) and chloride (Cl^-) ions concentrations were measured using the same equipment with ion-sensors. HCO_3^- plasma concentration was derived from pCO_2 using Handerson-Hasselbach equation and BE was calculated from Hb, HCO_3^- and pH values by Van Skyle equation (Lang et al., 2002).

The SID was calculated according to following equation (Stewart, 1983).

$$\text{Equation 1:} \quad [SID] = ([Na^+]+[K^+])-([Cl^-]+[Lac^-])$$

Test 3. Maximal incremental test

Seventy-two hours following the time trial, all athletes performed a maximal incremental test on a treadmill set at a 1% grade, with speed increments of 0.3 $km \cdot h^{-1}$ every 25 seconds until volitional exhaustion(Lourenço et al., 2011).

Oxygen uptake (VO_2), carbon dioxide production (VCO_2), breathing frequency (Bf) and tidal volume (Vt) were continuously measured in a breath-by-breath system (CPX/D Med Graphics, St. Paul, MN). Data was smoothed by averaging each 25-second interval as recommended (Robergs et al., 2010). The analyser was calibrated before each test using a known gas mixture (12% O_2 and 5% CO_2), and the volume sensor was calibrated using a 3-L syringe. Laboratory conditions were set a at 21 ± 1°C with relative humidity between 45-50%.

VT and RCP determinations

The ventilatory threshold running speed (sVT) and sRCP were determined using the V-Slope method (Beaver et al., 1986) through visual inspection by three independent and experienced researchers. VO_{2max} and the speed of VO_{2max} (sVO_{2max}) were identified as the values corresponding to the last stage completed with respiratory exchange ratio (RER) greater than 1.10 (D C Poole et al., 2008).

Analysis

Data are presented as mean ± SEM. Differences between AR and ER groups were assessed using unpaired t-tests. Pearson's correlation coefficient was calculated to determine association between blood variables and running test parameters. Correlations magnitudes were interpreted using the following scale: <0.1, trivial; 0.1–0.29, small; 0.3–0.49, moderate; 0.5–0.69, strong; 0.7–0.9, very strong; >0.9, nearly perfect (Hopkins et al., 2009). Statistical significance was set at 5% ($p < .05$).

RESULTS

Ventilatory parameters and 10-km time trial

Elite runners (ER) exhibited significantly higher s10km compared to amateur runners (AR) ($p < .05$; t = -11.22), as well as higher sVT ($p < .05$; t = -12.10); sRCP ($p < .05$; t = -11.98) and sVO_{2max} ($p < .05$; t = -8.91). sVT was significantly lower and sVO_{2max} significantly higher than the s10km in both groups ($p < .05$; t = -13.78), while no differences were observed between s10-km and sRCP ($p = .65$; F = -1.39).

Table 1. Respiratory parameters related to maximal incremental test and 10-km running performance of amateur and elite runners. Data are available in mean ± standard deviation.

	AR (n = 26)	ER (n = 20)
Mean 10 km running speed ($km \cdot h^{-1}$)	13.4 ± 1.4^{f}	$18.4 \pm 1.6^{f*}$
sVT ($km \cdot h^{-1}$)	11.5 ± 1.1	$15.9 \pm 1.0^{*}$
sRCP ($km \cdot h^{-1}$)	13.2 ± 1.3^{f}	$18.4 \pm 1.2^{f*}$
sVO_{2max} ($km \cdot h^{-1}$)	$16.7 \pm 1.2^{f\#}$	$21.4 \pm 1.7^{f\#*}$
VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)	57.5 ± 9.6	$75.8 \pm 5.4^{*}$

Note.-p < .05 related to AR;f-p < .05 related to sVT;#-p < .05 related to sRCP; sVT-Running speed related to ventilatory threshold; sRCP-Running speed related to respiratory compensation point;sVO2max-Running speed related to maximal oxygen consumption.*

Blood parameters

No significant differences between elite and amateur runners for resting pH, Lac^-, Hb and Hct ($p < .05$). However, BE, pCO_2 and Cl^- and HCO_3^- concentrations were significantly higher in ER ($p < .05$; Table 2) and Na^+ concentration and SID were significantly higher in AR ($p < .05$).

Correlation analyses revelled nearly perfect positive associations between s10-km and ventilatory parameters, with the strongest correlation being between sRCP (0.96; $p < .05$) and s10-km followed by sVT (0.95; $p < .05$) and sVO_{2max} (0.94; $p < .05$) (Table 3). Strong relationships were also observed certain acid-base parameters and 10-km. Resting HCO_3^- concentrations were strongly correlated with 10-km performance (r = 0.74; *p* < .05) and with all cardiorespiratory parameters (sVT, sRCP and sVO_{2max}). pCO_2 exhibited a strong relationship with 10-km performance (r = 0.68; *p* < .05) and sRCP (r = 0.68; *p* < .05), and a very large relationship with sVT (r = 0.71; *p* < .05) and sVO_{2max} (r = 0.76). SID showed a very strong negative relationship with all performance parameters except for sRCP (r = -0.67; *p* < .05).

Table 2. Rest acid-base blood profile and coefficients of analytical variation (CVA) of amateur (AR) and elite (ER). Data are available in mean ± standard deviation.

Parameter	AR	ER	CVA (%)
Hb (g/dL)	15.2 ± 0.9	14.8 ± 0.8	1.4
BE (mmol/L)	3.21 ± 1.43	5.6 ± 1.6*	-
HCO_{3-} (mmol/L)	25.7 ± 1.65	28.3 ± 2.0*	-
Hct (%)	45.7 ± 2.9	44.4 ± 2.7	3.2
K^+ (mEq/L)	5.27 ± 0.72	5.18 ± 1.0	0.4
Lac^- (mmol/L)	2.86 ± 0.86	2.59 ± 0.9	4.9
Na^+ (mEq/L)	143.5 ± 3.3	140.0 ± 4.1*	0.7
Cl^- (mmol/L)	100.1 ± 3.89	104.4 ± 3.83*	0.2
pCO_2 (mmHg)	33.9 ± 2.9	36.9 ± 3.7*	7.2
pH	7.47 ± 0.02	7.48 ± 0.03	0.9
SID	49.0 ± 5.70	41.3 ± 5.23*	-

*Note. Hb–haemoglobin; BE–base excess; HCO_{3-}-bicarbonate ion; Hct–haematocrit; K^+-potassium ion; Lac^--lactate ion; Na^+-sodium ion; Cl^--chloride ion; pCO_2–CO_2 partial pressure; SID–strong ion difference; *-significant difference in relation to AR.*

Table 3. Coefficient of correlation (r) among the blood acid-base parameters, 10-km running performance and running speeds related to the VT, RCP and VO_{2max}.

	s10km	sVT	sRCP	sVO_{2max}	BE	Hb	HCO_{3-}	pCO_2	pH	SID
s10 km	-									
sVT	.95*	-								
sRCP	.96*	.96*	-							
sVO_{2max}	.94*	.94*	.95*	-						
BE	.54*	.54*	.51*	.48*	-					
Hb	.40*	.40*	.44*	.52*	.03	-				
HCO_{3-}	.74*	.78*	.75*	.82*	.61	.58*	-			
pCO_2	.68*	.71*	.68*	.76*	.51	.52	.94*	-		
pH	.57*	.62*	.61*	.71*	.15	.75*	.85*	.77	-	
SID	-.70*	-.72*	-.67*	-.71*	-.64	.81*	-.69	-.65	-.02	-

*Note. 10-km-10-km running speed; Lac^--Lactate ion; SID-Strong ion difference; pH-blood pH; pCO_2-Carbonic dioxide partial pressure; Hct-Haematocrit; Hb-Haemoglobin; HCO_{3-}-Bicarbonate ion; BE-Base excess; sVT-Running speed related to ventilatory threshold; sRCP-Running speed related to respiratory compensation point; sVO_{2max}-Running speed related to maximal oxygen consumption. * p < .05.*

DISCUSSION

We hypothesized that indicator of the blood buffering capacity at rest (e.g., HCO_3^- and/or BE) could be positively correlated with endurance performance. Our primary finding is that SID and HCO_3^- concentrations were strongly related with 10-km running speed. To our knowledge, these results are the first to describe these relationships and compare acid-base status at rest between amateur and elite athletes.

Exercise training is known to stimulate mitochondrial biogenesis in skeletal muscle (Freyssenet et al., 1996). Furthermore, acute bicarbonate supplementation has been associated with increased blood buffering capacity and improved high-intensity exercise performance in exercises lasting to 1-7 minutes(Grgic et al., 2021; Hadzic et al., 2019). However, no studies have specifically investigated the relationship between resting HCO_3^- concentration and endurance performance or training status.

Jones (2008) reported that endurance training leads to a reduction in CO_2 output (VCO_2), a modest increase in arterial pCO_2 ($PaCO_2$) and elevated HCO_3^- during submaximal exercise. Previous studies (Tas et al., 2019; Zoll et al., 2006) also reported that carbonic anhydrase (CA) activity can increase by 50% after 6 weeks of continuous or interval training. Our data align with these findings, as elite runners showed higher pCO_2 and HCO_3 values at rest.

Within erythrocytes, CO_2 is hydrated by CA to form HCO_3^- and H^+. HCO_3^- ions are transported out via AE1 transporter while haemoglobin buffers H^+ (Geers et al., 2000). Studies have shown that endurance training not only increases CA transcription (Ponsot et al., 2006), but also enhances AE1 (Juel et al., 2003) expression, facilitating HCO_3^- transport to plasma to further support its buffering function in blood(Putman et al., 2003). This may also explain the strong relationship between resting HCO_3^- concentration and sRCP observed in this study. Since runners maintain speeds close to sRCP for nearly the entire race time (30 to 45 minutes) (Lourenço et al., 2019b) with blood pH stable, the maintenance of HCO_3^- concentration is crucial. These findings suggest that monitoring resting blood bicarbonate concentrations could serve as a predictor of performance or training-induced adaptations. BE, representing a non-respiratory (metabolic) component of acid–base status, indicates that endurance training also contributes to buffering agents beyond HCO_3^- , such as plasma proteins and haemoglobin (Zander et al., 2004).

SID, as an independent variable in the physicochemical approach, represents the sum of strong acid anions and strong base cations (Greenbaum et al., 2005). Both groups, amateur and elite runners, showed higher SID values compared to clinical reference values for healthy people (39 ± 1 mmol/L) (Kellum, 2005). Higher SID values increase blood pH (alkalosis), suggesting that endurance training induces adaptations in this system. Lower SID values in elite runners particularly due to lower Na+ concentrations, were observed.

On the other hand, it is well established that Cl^- plays essential roles in cell physiology, varying distributions across plasma membranes. Cells actively manage Cl^- levels, with some extruding and others actively accumulating it. The Cl^- concentration is influenced by anion transporting proteins such as AE1, which mediates Cl^- and HCO_3^- exchange in rate of 1 Cl^-:2 HCO_3^- in red blood cell (Geers et al., 2000). This may also explain the difference in SID values found in this study, once to favour HCO_3^- output from red blood cells, will be necessary higher Cl^- concentration in blood. However, further studies are needed to clarify the importance of SID on this issue. We also suggest studies that investigate these parameters with resting blood sample collected immediately before both, 10-km running and incremental exercise. A potential limitation of the study was the timing of the resting blood sample collection, which occurred two days after the 10-km test.

CONCLUSION

In conclusion, resting blood HCO_3^- concentration, along with other acid-base monitoring tools such as base excess and strong ion difference, is related to endurance performance. Endurance training induces adaptations that may enhance plasma buffering capacity, supporting higher exercise intensities during training and competition. Monitoring these adaptations at rest could provide valuable insights into training effectiveness and performance potential.

AUTHOR CONTRIBUTIONS

All authors contributed to all stages of the project including the writing of this manuscript. All authors have read and agreed to the published version of the manuscript. Thiago Fernando Lourenço conceived, and designed the study, collected the data, analysed, and interpreted the data, wrote the paper. Lazaro Alessandro Soares Nunes collected the data, interpreted the data, wrote the paper while Guilherme G. Artioli, Luiz E. B. Martins and Denise Vaz de Macedo interpreted the data and wrote the paper.

SUPPORTING AGENCIES

This work was supported by the São Paulo Research Foundation under Grant 03/09923-2P, National Council for Scientific and Technological Development under Grant 523383-96-7; and Development Foundation of UNICAMP under Grant 927.7.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Rehabilitation protocol with VISS (Vibration Sound System) following ankle sprain

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ABSTRACT

Introduction: Ankle sprain is one of the most frequent injuries in physically active people and the most common among lower extremity injuries. Although about 50% of these injuries are minor and resolve within a week, between 32% and 74% of subjects develop persistent symptoms such as pain, swelling, a feeling of sagging and reduced function, and recurrent sprains within 12 months of the first event. This set of symptoms is referred to as chronic ankle instability. Materials and Methods: This study included 30 subjects aged between 20 and 35 years. The subjects were initially divided into two groups: the experimental group followed a 4-week protocol with VISS, while the control group completed a 4-week protocol of proprioceptive and balance exercises. Results: The research protocol demonstrated that the 6-week VISS protocol is effective in improving the pathological condition of Chronic Ankle Instability (CAI), resulting in enhanced muscle tone, reduced pain, and a decreased perception of instability. Conclusions: Although limited by the sample size, the results of this study provide a starting point for future research.
Keywords: Sport medicine, Athletes, Rehabilitation, Extremity injury.

Cite this article as:
Barbato, C., Coppola, R., Bruni, D., Stradaioli, R., Gervasi, M., & Bellomo, R. G. (2025). Rehabilitation protocol with VISS (Vibration Sound System) following ankle sprain. *Journal of Human Sport and Exercise, 20*(2), 479-490. https://doi.org/10.55860/6pth6f95

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Submitted for publication November 13, 2024.
Accepted for publication December 20, 2024.
Published February 10, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/6pth6f95

INTRODUCTION

The incidence of ankle sprains is notably high (Doherty et al., 2013). In the United Kingdom, ankle sprains account for approximately 3% to 5% of all emergency department visits, translating to around 5,600 ankle sprain cases per day (Cooke et al., 2003 in Doherty et al., 2013).

From an economic perspective, ankle sprains result in significant costs, as roughly one-quarter of individuals who experience a sprain are unable to attend work or school for at least 7 days following the initial injury (RA de Bie et al., 1997 in Doherty et al., 2013).

A 2016 survey involving a sample of 225,000 individuals who presented to emergency departments for ankle sprains highlighted variations in incidence across age groups (Martin et al., 2021). Among those surveyed, 27% were under 18 years old, 40% were aged 18 to 35, 18% were between 36 and 49, and the remaining 15% were over 49 years of age (Martin et al., 2021).

Ankle injuries are highly prevalent in sports. Research found that between 2002 and 2006, approximately 3,140,132 ankle sprains occurred in the United States, with the highest incidence observed in individuals aged 15 to 19 years (Waterman et al., 2010). Among those aged 15 to 24, there was no significant difference in incidence between males and females, though a higher prevalence was found in females over age 30 (Waterman et al., 2010). About half of the ankle sprains in this population occurred during sports activities, such as basketball, soccer, and athletics (Waterman et al., 2010).

Furthermore, as many as 70% of individuals who have experienced an initial ankle sprain may suffer from a subsequent sprain or continue to experience symptoms such as weakness, a sense of instability, and pain. This condition is referred to as chronic ankle instability (CAI) (Sefton J.M., et al., 2011). While ankle sprains are common across the general population, their frequency increases significantly among physically active or sports-engaged individuals. In fact, ankle sprains are the second most frequent injury in athletes, and recurrent sprains often have a history of prior sprains (McKeon P.O., Hertel J., 2008).

Approximately 70% of individuals who sustain an initial ankle sprain are at risk of developing CAI within a short period (Herzog et al., 2019). Recent studies indicate that between 15% and 64% of individuals with an initial ankle sprain continue to experience unresolved symptoms three years post-injury (Jull et al., 2015). This systematic review further noted that roughly 8% of patients in the general population report long-term issues persisting up to ten years (Jull et al., 2015).

In 2016, the International Ankle Consortium released a consensus statement and evidence review addressing the prevalence, impact, and long-term consequences of lateral ankle sprains (Gribble PA., et al., 2016). These publications provide an evidence base regarding lateral ankle sprains, CAI, and the associated direct and indirect costs, setting specific objectives for future research.

CAI affects not only the ankle but can also systematically impair other joints, leading to additional physical complications (Hertel J., et al., 2019). In individuals with CAI, the ankle structure exhibits reduced range of motion, secondary tissue damage, restricted osteokinematics, and post-traumatic osteoarthritis (Hertel J., et al., 2019). CAI adversely impacts proprioception, balance, movement patterns, and results in muscular weakness and bilateral reflex impairment (Hertel J., et al., 2019). Additionally, it can predispose individuals to further injuries, such as recurrent ankle sprains, early onset osteoarthritis, and increased stress on the anterior cruciate ligament (Gribble PA., et al., 2016).

Due to the numerous adverse outcomes associated with CAI, implementing a preventive strategy is essential, with epidemiological data playing a critical role (Bahr R., Krosshaug T., 2005). In a meta-analysis, Doherty C., et al. (2014) reported an incidence rate of 0.93 per 1,000 athlete exposures (AE, where 1 AE is defined as 1 athlete participating in 1 competition or training session). By comparison, the incidence rates for acute medial and high/syndesmotic ankle sprains were lower, at approximately 0.06 and 0.38 per 1,000 AE, respectively (Doherty C., et al., 2014).

Indeed, more than three-quarters of all acute ankle sprains are lateral ankle sprains, with roughly 73% affecting the anterior talofibular ligament (Fong DT., et al., 2007). Of the remaining acute ankle sprains, 25% are medial (involving the deltoid ligament) or high/syndesmotic (affecting the anterior-inferior or posterior-inferior tibiofibular ligaments).

MATERIALS AND METHODS

The research group consisted of 30 subjects aged between 20 and 35 years. Subjects were selected based on the following inclusion criteria:

- Aged between 22 and 30 years;
- Diagnosed with a grade 1 or 2 ankle sprain.

Exclusion criteria included:

- Subjects with multiple injuries;
- Subjects with other conditions limiting mobility;
- Subjects with ankle injuries requiring immobilization;
- Subjects unable to follow the rehabilitation protocol.

Participants were initially divided into two groups: the experimental group followed a 4-week protocol with VISS (Vibration Intervention System for Strength), while the control group followed a 4-week protocol of proprioceptive and balance exercises.

After selection, subjects underwent two physical tests (the talar tilt test and the anterior drawer test) and completed two questionnaires, the SF-36 and Cumberland questionnaires, along with the VAS scale. Following the preliminary assessment, the subjects, grouped into two cohorts, began the respective protocols.

The experimental group underwent a 6-week VISS protocol with two sessions per week. During these sessions, the 15 subjects received VISS treatment. VISS is designed to enhance physical strength, increase muscular endurance, and improve coordination through a high-tech system based on the mechanical and sonic action of vibrations. When applied to localized muscle regions, it optimizes muscle tone, increases resistance to muscular load, and improves coordination.

The first six sessions, each lasting approximately 30 minutes, included:

- The first 10 minutes at 300 Hz to enhance muscle strength;
- The next 10 minutes at 200 Hz to normalize muscle tone;
- The final 10 minutes at 120 Hz to relax, relieve fatigue, and target trigger points.

The final six sessions were 30 minutes each at 300 Hz. For optimal transmission of vibration to the skin, pen-shaped transducers were used to better adhere to smaller areas and target trigger points. This transmission was safe and controlled, allowing the therapist to adjust the intensity and frequency of vibrations according to each patient's needs.

Figure 1. Vibration sound system and transducers.

The control group followed a 6-week protocol, with two sessions per week, where the 15 participants engaged in physical activity sessions that included exercises for stretching, proprioception, balance, and muscle strengthening.

The goal of the protocol was to achieve the full range of motion for the joint and to restore specific pain-free movement, along with coordination recovery and complete body awareness.

Each session lasted approximately 50 minutes, consisting of a 10-minute warm-up, a 30-minute main segment, and a 10-minute cooldown.

During the warm-up, exercises such as walking, high-knee walking, and walking on toes and heels were performed.

The main phase included exercises such as plantar and dorsal flexion, and internal and external rotation using resistance bands.

Perform ground-based heel raises, initially with bilateral support, then progressing to single-leg support, and finally using a Bosu ball to increase the exercise difficulty. Complete 15 repetitions per exercise, for 3 sets.

Proprioceptive exercises in a non-weight-bearing position, using a proprioceptive balance board. The subject is seated and instructed to perform ankle flexion-extension, inversion, and eversion movements.

Balance training on BOSU or balance board

Initially, balance exercises are performed in a bipodal (two-legged) stance, progressing to a unipodal (single-legged) stance. Each stance is maintained for 20 seconds, with 4 sets in total.

Proprioceptive load-bearing exercises

Using a proprioceptive balance board, single-leg balance exercises are performed with the ankle moving through plantar flexion and dorsiflexion, as well as abduction and adduction.

Figure 2. 12 repetitions per exercise, for 3 sets.

Figure 3. 12 repetitions per exercise, for 3 sets, balance training.

RESULTS

The symmetry and kurtosis analysis tests, along with the Kolmogorov-Smirnov normality test, confirm the normal distribution of the data ($p < .0001$). Therefore, parametric tests are employed to investigate differences between groups as well as the effectiveness of the experimental protocol and motor protocol.

The analysed variables pertain to three measurements:

1. Drawer Test (1 item)
2. Talar Tilt Test (3 items)
   a. Inversion
   b. Neutral
   c. Eversion
3. SF36 Questionnaire (36 items – 8 variables)
   a. Physical functioning
   b. Physical health limitations
   c. Emotional health limitations
   d. Energy and fatigue
   e. Emotional well-being
   f. Social functioning
   g. Pain
   h. General health perception

Table 1 presents the mean, standard deviation, and standard error for all variables, segmented by group (experimental VISS and control) and time (pre- and post-treatment).

Table 1. Descriptive statistics - mean, standard deviation, and standard error of distinct variables, categorized by group (experimental and control) and time (pre- and post-treatment).

		Control Group			Experimental Group (Viss)		
Variable	**Time**	**Mean**	**Std. Deviation**	**Std. Error Mean**	**Mean**	**Std. Deviation**	**Std. Error Mean**
Drawer test	Pre	0.000	0.000	0.000	0.000	0.000	0.000
	Post	0.07	0.067	0.258	1.00	0.000	0.000
Inversion	Pre	0.000	0.000	0.000	0.000	0.000	0.000
	Post	0.000	0.000	0.000	1.00	0.000	0.000
Normal	Pre	0.000	0.000	0.000	0.07	0.07	0.258
	Post	0.13	0.091	0.352	1.00	0.000	0.000
Eversion	Pre	0.000	0.000	0.000	0.000	0.000	0.000
	Post	0.07	0.067	0.258	1.00	0.000	0.000
SF36_ Physical functioning	Pre	10.00	5.35	20.70	3.33	3.33	12.91
	Post	16.67	6.29	24.39	99.67	0.33	1.29
SF36_ Physical health limitation	Pre	0.000	0.000	0.000	0.000	0.000	0.000
	Post	0.000	0.000	0.000	99.17	0.83	3.23
SF36_ limitations emotional problems	Pre	0.000	0.000	0.000	0.000	0.000	0.000
	Post	0.000	0.000	0.000	100.00	0.00	0.00
SF36_ Energy Fatigue	Pre	9.67	2.46	9.54	4.67	1.91	7.43
	Post	6.67	2.52	9.76	97.50	1.34	5.18
SF36_ Emotional well-being	Pre	5.87	2.27	8.79	11.47	2.56	9.89
	Post	5.33	2.36	9.15	100.00	0.00	0.00
SF36_ Social functioning	Pre	6.67	2.95	11.44	13.33	3.10	12.01
	Post	13.33	3.33	12.91	98.33	1.67	6.46
SF36_Pain	Pre	7.50	2.83	10.98	13.50	2.95	11.41
	Post	7.50	2.83	10.98	100.00	0.00	0.00
SF36_ General health	Pre	12.67	2.84	10.99	5.67	2.43	9.42
	Post	7.67	2.83	10.99	99.33	0.67	2.58

First, the differences between the two groups were examined both before and after the treatment, and the results are presented in Table 2.

Table 2. t- t-test; differences between the two groups (Control group and Viss group) before treatment (pre-treatment) and after treatment (post-treatment).

	Pre		Post	
Variable	**t**	**sig.**	**t**	**sig.**
Drawer test	-	-	-14.00	<.001
Inversion	-	-	-	-
Normal	-1.00	>.05	-9.54	<.001
Eversion	-	-	-14.00	<.001
SF36_ Physical functioning	1.059	>.05	-13.16	<.001
SF36_ Physical health limitation	-	-	-119.00	<.001
SF36_ Limitations emotional problems	-	-	-	-
SF36_ Energy Fatigue	1.60	>.05	-31.85	<.001
SF36_ Emotional well-being	-1.64	>.05	-40.05	<.001
SF36_ Social functioning	-1.56	>.05	-22.81	<.001
SF36_Pain	-1.47	>.05	-32.63	<.001
SF36_ General health	1.87	>.05	-31.43	<.001

Note. The variables with no values showed the same results between pre and post, making it impossible to calculate the t-value.

It can be observed that initially the two groups did not show statistically significant differences for all the variables considered. However, after the treatment, statistically significant differences were found for almost all the variables. Since no differences were observed for all the variables, a t-test was performed by dividing the sample into groups to assess the effectiveness of the treatment with Viss (control and Viss).

Table 3. Independent samples t-test. Effects of therapy using Viss on the sample (difference between pre- and post-treatment).

	Control Group		Viss Group	
Variable	**t**	**sig.**	**t**	**sig.**
Drawer test	-1.00	>.05	-	-
Inversion	-	-	-	-
Normal	-1.47	>.05	-14.00	<.001
Eversion	-1.00	>.05	-	-
SF36_ Physical functioning	-0.807	>.05	-28.76	<.001
SF36_ Physical health limitation	-	-	-119.00	<.001
SF36_ Limitations emotional problems	-	-	-	-
SF36_ Energy Fatigue	0.852	>.05	-39.69	<.001
SF36_ Emotional well-being	1.00	>.05	-34.64	<.001
SF36_ Social functioning	0.067	>.05	-24.14	<.001
SF36_Pain	1.00	>.05	-29.36	<.001
SF36_ General health	0.35	>.05	-37.13	<.001

This table highlights the findings presented in the previous one, as the experimental group shows significant results, indicating an improvement in nearly all the analysed variables.

CONCLUSIONS

The objective of this study is to analyse the effectiveness of the VISS protocol in the treatment of chronic ankle instability (CAI). Specifically, pain, the perception of instability, strength, and muscle tone were evaluated. The research protocol revealed that the 6-week VISS protocol is effective in improving the pathological condition of CAI, leading to enhanced muscle tone, reduced pain, and a lower perception of instability. Although the results of this study are limited by the sample size, they provide a starting point for future research, where the sample size could be expanded and a third group could be included, incorporating a multidisciplinary approach with other specialists (for instance, to address aspects related to the "*Emotional Issues*" variable).

AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. All authors read and approved the final manuscript.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ETHICS APPROVAL

This study was performed in line with the principles of the Declaration of Helsinki. Written informed consent was obtained from the parents.

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ORIGINAL ARTICLE

Postural control impairment in young competitive badminton players with knee injuries: A comparative study on balance deficits

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ABSTRACT

Balance is critical, particularly in high-paced sports like badminton, where quick movements are frequent. The purpose of this study is to explore how knee injuries affect the balance, both static and dynamic, of badminton players compared to their healthy counterparts. This cross-sectional study recruited 80 male badminton players with 40 in the knee injury group (KIG) and 40 in the healthy group (HG). Static and dynamic balance was analysed using balance error scoring system (BESS) and Y-balance test (YBT) respectively. An independent t-test was used to analyse the significant difference in both static and dynamic balance between two groups. BESS showed significant difference between both groups in tandem stance (p = .00) and total BESS scores on the firm surface (p = .00). The YBT showed significant changes only in the anterior direction between the group, for dominant leg (p = .001) and non-dominant leg (p = .001). No significant differences were observed in other directions. Players with knee injuries show postural control impairments, including higher errors and reduced anterior reach exhibiting a potential health risk. These deficits compromise static and dynamic balance, emphasizing the need for targeted balance training and rehabilitation intervention.
Keywords: Sport medicine, Dynamic balance, Sports performance, Postural stability, Knee pathology, Health risk.

Cite this article as:
Purushothaman, V. K., Ramalingam, V., Diong, H. T., Subbarayalu, A. V., Marimuthu, P. R., Orhan, B. E., & Purushothaman, S. (2025). Postural control impairment in young competitive badminton players with knee injuries: A comparative study on balance deficits. *Journal of Human Sport and Exercise, 20*(2), 491-498. https://doi.org/10.55860/3715gw39

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Submitted for publication November 26, 2024.
Accepted for publication January 10, 2025.
Published February 10, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/3715gw39

INTRODUCTION

Maintaining postural stability and dynamic balance is essential for athletes, especially in sports characterized by quick movements and abrupt changes in direction, such as badminton. Postural stability is the capacity to keep the body's centre of mass within the base of support, while dynamic balance is the ability to manage body position while in motion (Malwanage et al., 2022).These elements are vital for achieving the best possible performance and avoiding injuries in badminton, a sport that requires agility, rapid reaction times, and accurate footwork. Research has indicated that lower limb injuries make up 40-80% of all badminton injuries, with the anterior cruciate ligament being the most severe damage to the lower limb (Marchena-Rodriguez et al., 2020). The most prevalent injuries among badminton players are knee joint, followed by injuries to the back, ankle joint, and knee joint (Kang & Ramalingam, 2018). The most prevalent knee joint injury is the anterior cruciate ligament (ACL) damage, with noncontact incidents accounting for 70% of all ACL injuries. Landing and sudden changes in direction primarily cause these injuries (Reeves et al., 2015).

Competitive badminton players often sustain lower-limb injuries, including knee injuries, which can affect their postural stability and dynamic balance (Pardiwala et al., 2020). Knee joint injuries can result in reduced proprioception, decreasing muscle strength and impaired neuromuscular control. The sensorimotor system primarily governs the functional stability of the knee joint during voluntary movement. As a dynamic system, it plays a role in transmitting and combining somatosensory, vestibular, and visual information to the central nervous system, allowing for adaptation to the environment (Solomonow & Krogsgaard, 2001). Changes in incoming sensory information, which could be due to damage to mechanoreceptors around the joint, can then lead to disruptions in sensorimotor control (Adachi et al., 2002). These factors can have a detrimental effect on an athlete's balance and their ability to perform the quick, multi-directional movements necessary in badminton (Alikhani et al., 2019). Nevertheless, conflicting results suggest that these changes may not necessarily be associated with the ability to maintain balance while standing (Lee et al., 2015). Earlier literature observed a significant relationship between previous lower limb injury and dynamic balance using modified star excursion test (Kurihara et al., 2024). Evidence strongly indicates that individuals with lower limb injuries experience a significant decrease in postural stability. In addition, the degree of sway during single leg stance was considerably increased in the group with lower limb injuries compared to the healthy individuals (Lehmann et al., 2017).

Understanding the differences in postural stability and dynamic balance between badminton players with and without knee injuries can inform targeted rehabilitation and injury prevention strategies. Previous research has highlighted the importance of footwork and agile reactions in badminton performance (Kuo et al., 2022). Studies have also emphasized the role of anthropometric factors, such as arm length and wrist flexibility, in determining badminton skill level (Jaworski & Żak, 2015). However, there is a paucity of research directly comparing postural stability and dynamic balance between young, competitive badminton players with and without knee injuries. In view of this, the current study aimed to investigate the difference in static and dynamic balance between injured and non-injured young competitive badminton players.

METHODS

Participants

This cross-sectional study recruited 80 young male competitive badminton players, aged between 18 and 25, from 4 local badminton academic clubs in the Klang valley, Malaysia. The participants were selected using a purposive sample method. To meet the inclusion criteria the participants must be registered academic club players, have competed in at least two national tournaments, experienced a knee injury and had caused them to stop participating in sports and cured 6 months before the beginning of this study. Participants with the history of vestibular disorders, lower limb fractures and surgery were excluded from the study. The participants were allocated into two groups of 40 each: the knee injury group (KIG), consisting of participants who have previously suffered a knee injury, and the healthy group (HG), consisting of individuals who have not encountered any knee injuries.

Sample size estimation

The required sample size was determined using the GPower 3.1 software, and it was observed to be 40 participants in each group, keeping the effect size (ρ) of 0.3, using a two-tailed test with a power of 0.80 (1-β) (Faul et al., 2007).

Ethical approval

The study obtained ethical approval from the Institutional Research and Ethical Committee with reference number INTI-IU/FHLS-RC/BPHTI/7NY12022/004 prior to commencing the project. The objectives, potential benefits, and risks of the study were explicitly communicated to all participants, and their informed consent was obtained.

Outcome measurement

Balance Error Scoring System (BESS)

The BESS has moderate to good reliability to assess static balance (Bell et al., 2011). The balance assessment involves three postures performed on two distinct surfaces: a firm and a foam surface. The three postures consist of the double leg stance, single leg stance, and tandem stance. The athlete will assume a stance with hands placed on hips, eyes closed, and feet consistently positioned according to the chosen stance, without wearing shoes. In the double leg stance, the feet are positioned flat on the testing surface, with approximately the width of the pelvis between them. During the single leg stance, the athlete should balance on their non-dominant leg while keeping the opposite leg bent at the hip by about 20°, at the knee by about 45°, and in a neutral posture in relation to the body's side-to-side movement. In the tandem stance, one foot is placed in front of the other with heel of the anterior foot touching the toe of the posterior foot. The athlete’s non-dominant leg is in the posterior position. The duration of the trial is 20 seconds. Determine the quantity of errors while maintaining the correct posture. The examiner should commence counting mistakes once the individual has taken up the appropriate testing posture. When numerous faults happen simultaneously, just one of them is considered. The maximum allowed number of errors for a single condition is 10. A number ranging from 0 to 60 is used to measure balance and error rate, with lower values indicating greater balance and fewer errors. The sum of errors in each trial is calculated to determine the final score, which is measured on a scale of 60.

Y Balance Test (YBT)

The Y Balance Test (YBT) is a test that assesses dynamic balance and risk of injury by having the athlete balance on one leg and reach as far as possible in three directions: anterior, posteromedial and posterolateral. The athlete should be directed to place their hands on their hips and slide the first box forward using their right foot as far as possible before returning to the starting position. The distance reached must be measured in centimetres. They must then repeat this process with the same foot three times. Once they have successfully completed three reaches with their right foot, they may proceed to do the same with their left foot. When the athlete has completed three successful reaches on both feet, they can move on to the next direction for testing. The YBT showed good interrater test-retest reliability with an acceptable level of measurement error among multiple raters with excellent reliability (ICC = 0.88- 0.99)(Shaffer et al., 2013).

The relative reach distance was calculated using by: Relative reach distance (%) = Absolute reach distance / limb length * 100.

Data analysis

The data collected were analysed using IBM SPSS Statistics, version 26.0 (IBM Corporation, Armonk, NY, USA). Continuous data was represented in mean and standard deviation. An independent t-test was employed to analyse the significant difference in static and dynamic balance between two groups.

RESULTS

A total of 40 subjects in this study with a mean age of 20.70 ± 2.68 years, with BMI 21.90 ± 2.69 were recruited. Their mean training days are 5.27 ± 1.63 per week, with 14.17 ± 5.69 of training hours. The subjects participated in approximately 2 competitions per month. The demographic characteristics of the participants for the two groups were presented in Table 1.

Table 1. Demographic of the participants.

	KIG (N = 40) (Mean ± SD)	HG (N = 40) (Mean ± SD)
Age	21.90 ± 2.47	19.70 ± 2.35
BMI	22.62 ± 2.90	21.36 ± 2.39
Training days/week	5.35 ± 1.61	5.15 ± 1.74
Training hours/week	15.63 ± 4.75	12.67 ± 6.30
Competitions/month	2.30 ± 0.46	2.15 ± 0.53

Note. BMI- Body Mass Index, SD- Standard deviation.

Table 2. Comparison of balance tests scores between injured and healthy group.

Outcomes	KIG (N = 40) (Mean ± SD)	HG (N = 40) (Mean ± SD)	t-value	*p*-value
BESS	9.03 ± 1.56	7.60 ± 1.63	3.99	.00*
YBT (D)	81.75 ± 10.07	86.73 ± 11.63	2.04	.04*
YBT (ND)	82.40 ± 11.82	86.63 ± 12.93	1.67	.09

*Note. *D = dominant leg; ND = non-dominant leg, BESS – Balance Error Scores, YBT – Y Balance Test.*Statistically significant difference between groups (p < .05).*

Table 2 determined that there was a statistically significant difference between injured and uninjured players with regards to the total scores of BESS ($p < .05$). However, there was no significant difference between either group with regards to the total scores of YBT (D), and YBT (ND).

Table 3. BESS scores between injured and healthy group.

BESS	KIG (N = 40) (Mean ± SD)	HG (N = 40) (Mean ± SD)	t-value	*p*-value
Firm surface				
DL	0.13 ± 0.33	0.10 ± 0.30	0.35	.72
SL	1.50 ± 0.81	1.47 ± 0.64	0.15	.87
TS	1.15 ± 0.53	0.20 ± 0.40	8.96	.00*
Total	2.78 ± 0.891	1.77 ± 0.78	5.480	.00*
Foam surface				
DL	0.18 ± 0.38	0.23 ± 0.42	0.55	.58
SL	3.68 ± 0.82	3.25 ± 1.17	1.87	.06
TS	2.40 ± 0.59	2.35 ± 0.58	0.38	.70
Total	6.25 ± 0.95	5.82 ± 1.21	1.738	.86

*Note. *DL = double leg stance; SL = single leg stance; TS = tandem stance.*

According to the findings in Table 3, there was a statistically significant difference observed between injured and uninjured players in terms of the average values of firm surface tandem position. Additionally, there was also a statistically significant difference observed between injured and uninjured players in terms of the average values of total scores of firm surfaces. The statistical significance level was set at $p < .05$. Considering the YBT score between the dominant and non-dominant legs, except in the anterior direction ($p < .05$), all the other directions are found to be in-significant at .05 levels (Table 4).

Table 4. YBT scores between injured and healthy group.

YBT	KIG (N = 40) (Mean ± SD)	HG (N = 40) (Mean ± SD)	t-value	*p*-value
Dominant leg				
ANT	57.00 ± 5.79	62.08 ± 4.15	4.502	.001*
PM	61.65 ± 10.39	63.90 ± 10.24	0.957	.34
PL	63.68 ± 7.86	64.72 ± 10.64	0.502	.61
Non-dominant leg				
ANT	57.31 ± 4.70	61.75 ± 6.67	3.437	.001*
PM	62.70 ± 9.42	65.30 ± 9.97	1.199	.23
PL	63.52 ± 10.58	64.00 ± 9.36	0.213	.83

*Note. *ANT = anterior; PM = posteromedial; PL = posterolateral. *Statistically significant difference between groups (p > .05).*

DISCUSSION

This study highlights the considerable effect that knee injuries have on postural control and balance in the young, competitive badminton player. The significant differences observed in the static balance between injured and non-injured athletes, particularly in BESS scores, highlight how knee injuries affect proprioception and neuromuscular control. Injured players demonstrated definite postural instability on firm ground and in tandem, where these deficits were most obviously apparent. This finding is consistent with prior research demonstrating that knee injuries, particularly those affecting ACL, compromise proprioceptive feedback mechanisms, reducing an athlete's ability to maintain a stable stance (Adachi et al., 2002; Solomonow & Krogsgaard, 2001). This impairment likely results from damage to mechanoreceptors within the knee joint, which is critical for accurate joint positioning and balance (Al-Dadah et al., 2020; Haggerty et al., 2021; Zeng et al., 2022). With adequate sensory feedback, players can maintain stability, which is particularly challenging in a sport like badminton that requires rapid and agile movements (Lee et al., 2015; Pardiwala et al., 2020).

The observed deficiencies in dynamic balance, assessed via YBT, further illustrate the extent of impairment in injured players. Although the differences in YBT scores were significant only in the anterior reach direction, this finding is particularly relevant for badminton players, as anterior reach stability is crucial for forward lunges and quick directional changes (Kurihara et al., 2024; Powden et al., 2019). This directional-specific deficit might indicate a disruption in the anterior kinetic chain's neuromuscular coordination, potentially stemming from altered muscle activation patterns and joint positioning post-injury (Alikhani et al., 2019). This can predispose athletes to develop muscle imbalances following the recovery from knee injury due to adaptations in movement patterns to prevent stressing the injured knee. This adaptation may hinder the efficacy of forward and multi-directional movements, which are essential in badminton (Kuo et al., 2022). Therefore, rehabilitation protocols for injured badminton players should consider targeted interventions to restore anterior stability and strengthen proprioceptive control in the anterior reach direction (Jaworski & Żak, 2015; Reeves et al., 2015).

The results of this study carry essential implications for injury prevention and rehabilitation strategies in competitive badminton. For injury prevention, our findings suggest that targeted proprioceptive training exercises could mitigate the risk of knee injuries by enhancing neuromuscular control and balance (Arumugam et al., 2021; Ghaderi et al., 2020). Applying such balance training exercises on firm surfaces, particularly in tandem stance conditions, may enhance the body's sensorimotor control for injury prevention (Muehlbauer et al., 2012). Furthermore, the study's findings indicate that dynamic balance training should emphasize multi-directional stability, with particular attention to the anterior reach direction, to prepare athletes for the demands of the sport (Bell et al., 2011). Preventative programs could incorporate single-leg squats, lunges with balance components, and proprioceptive drills using wobble boards or foam surfaces to build resilience against injury (Jaworski & Żak, 2015).

For rehabilitation, these findings underscore the need for comprehensive balance assessments in athletes with knee injuries to better tailor post-injury programs. A focus on restoring proprioceptive function and improving neuromuscular control in the affected knee joint is crucial. Rehabilitation protocols could integrate static and dynamic balance exercises, progressing from simple stances to complex movements that mimic sports-specific demands. Exercises targeting single-leg stability, multi-directional lunges, and dynamic tasks on varied surfaces (such as foam and firm surfaces) may address the deficits observed in this study and restore functional balance. Moreover, training regimens that challenge the vestibular and visual systems could also prove beneficial, as these systems are integral to maintaining postural stability, particularly in dynamic sports environments (Malwanage et al., 2022).

The results of this study also add to the general knowledge of the association between knee injuries and postural control abnormalities. In the past, badminton was known for its requirement to be agile, have good reaction time, and have good footwork (Arnando et al., 2024; Kuo et al., 2022; Malwanage et al., 2022). However, this research found that balance was critical to achieving high-level performance and avoiding the recurrence of injury. The dynamic nature of badminton, which involves high-speed directional changes, frequent jumping, and sudden stops, places substantial demands on an athlete's postural stability. As a result, insights into balance deficits might give an athlete a competitive advantage and longevity (Han et al., 2022; Jaworski & Żak, 2015; Kuo et al., 2022).

The limitations of this study should be acknowledged. First, its cross-sectional design limits the ability to draw causal inferences between knee injuries and balance impairments. Longitudinal investigations would offer more information on how balance problems arise and evolve after a knee injury and how postural control changes as the injury evolves. Additionally, the study's sample was restricted to competitive badminton players aged 18–25, limiting the generalizability of the findings to other age groups and skill levels. Including a more diverse sample of athletes could help clarify whether these balance deficits are specific to younger, competitive players or extend across various age groups and experience levels. Finally, although the BESS and YBT are widely used to assess balance, further tests incorporating both proprioceptive and neuromuscular aspects of balance could provide a more complete picture of balance impairments in injured athletes. Future research could benefit from combining balance assessments with electromyography or motion analysis to capture neuromuscular activation patterns and joint kinematics better.

CONCLUSION

This study highlights knee injuries' significant impact on static and dynamic balance in young competitive badminton players. Injured players demonstrated considerable deficits in static balance, particularly in the tandem stance on firm surfaces, and showed reduced dynamic stability in the anterior reach direction. Therefore, balance-focused interventions should be incorporated in preventive and rehabilitative programmes for badminton players. By addressing balance deficits, coaches and rehabilitation professionals can improve postural control, reduce re-injury risks, and enhance athletic performance.

AUTHOR CONTRIBUTIONS

VKP,HTD - Data collection, conceptualization, writing original draft; VKR,AVS,PRM - Formal analysis, methodology & data curation; BEO & SP: Review & editing & literature review search.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Shoulder's strength, range of motion and scapulohumeral rhythm in a cohort of male master tennis players

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ABSTRACT

Tennis is known for its repetitive upper limb movements, which can potentially lead to injuries. While past research investigated shoulder biomechanics in young athletes and female players, there is a lack of study regarding male master tennis athletes. This study aimed to compare some of the biomechanical features in the dominant shoulder between master tennis players and age-matched non-tennis athletes. Isometric strength, range of motion, and scapulohumeral-rhythm, which describes the coordinated kinematic pattern between scapula and humerus during arm elevation, with and without 2kg dumbbells, were compared between 15 master tennis athletes and 15 non-tennis athletes. Tennis athletes exhibited a higher external rotation RoM in the dominant than in the non-dominant shoulder with no differences with non-tennis athletes. Extension, abduction, adduction and external rotation strength were greater in tennis athletes compared to controls, while there were no differences in the external to internal rotation ratio. Scapulohumeral-rhythm in the dominant shoulder was similar between the two groups, with a magnitude approaching the physiological value of 2:1. Therefore, from a biomechanical perspective, the results suggest that long-term participation in tennis does not significantly affect the balance in shoulder rotator strength and the scapulohumeral-rhythm, likely not representing a risk factor for shoulder injuries.
Keywords: Biomechanics, Injuries, Overhead, Scapular kinematic, Inertial sensors.

Cite this article as:
Bravi, M., Borzuola, R., Picerno, P., Vannozzi, G., Santacaterina, F., Giombini, A., Massazza, G., Riba, U., Papalia, R., Pigozzi, F., Fossati, C., & Macaluso, A. (2025). Shoulder's strength, range of motion and scapulohumeral rhythm in a cohort of male master tennis players. *Journal of Human Sport and Exercise, 20*(2), 499-514. https://doi.org/10.55860/97xntn93

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Submitted for publication November 05, 2024.
Accepted for publication December 17, 2024.
Published February 10, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/97xntn93

INTRODUCTION

Tennis has been defined as a "*lifetime sport*" because it promotes competition and participation throughout all ages of life (Spring et al., 2020). A recent report by the International Tennis Federation (*ITF - ITF Global Tennis Report 2021*, n.d.) estimated that 1.71% of the world population play tennis and that globally there are 87 million tennis players of which 41% are female, demonstrating its widespread diffusion all over the world. Furthermore, the Tennis Industry Association reported that the "*frequent player*" category (21-49 times/year) is represented by approximately 1.07 million players aged 50 and over (2019 TIA Tennis Participation Report, 2019).

Playing tennis regularly is associated with overall health benefits including better aerobic fitness, lower percentage of body fat concentration, and reduced risk of diabetes and cardiovascular diseases (Pluim et al., 2007; Swank et al., 1998). However, this sport requires repetitive movement patterns with overhead upper limb actions that can cause upper limb injuries (Abrams et al., 2012). Particularly, the shoulder is subject to high risk of injury in tennis as it constantly experiences high loads during the serve and overhead strokes. Moreover, this risk seems to be correlated with age and with the increase in skill level and participation frequency (Pluim et al., 2006). The underlying cause of shoulder symptoms appears to differ according to age. Specifically, older players tend to experience alterations that are predominantly related to the rotator cuff, whereas shoulder instability prevails among younger tennis players (Perkins & Davis, 2006).

Generally, it is not uncommon for tennis players to suffer from shoulder pain, which is often attributed to sport-specific adaptations, such as alterations in strength, flexibility and posture. These adaptations are not only related to the shoulder joint, but also to other joints that are involved in the kinetic chain of the sport gesture. Previous research has revealed a wide range of shoulder injuries, with percentages varying between 4% and 17%, across tennis players of all skill levels (Sallis et al., 2001; Sell et al., 2014; Winge et al., 1989). Loss of shoulder range of motion (RoM), impaired rotator cuff muscle balance, scapular dyskinesia and core muscle instability have been identified as the main factors that can cause an increased risk of injury in tennis players (Kibler et al., 2012; Kibler, 1998; Lintner et al., 2008; Silva et al., 2006, 2010). The scapula is a key element in shoulder biomechanics and is essential for a normal shoulder function. The scapulohumeral rhythm (SHR), which describes the coordinated kinematic pattern between the scapula and the humerus during arm elevation, is crucial for the transmitting force from the torso to the arm (Myers et al., 2005). Alterations of the SHR, known as scapular dyskinesis, disrupt shoulder biomechanics and appear to increase shoulder dysfunction due to a greater stress placed on the soft tissues in the shoulder complex (Kibler et al., 2012; Laudner et al., 2007).

Reducing the risk of injury is crucial to ensure tennis participation among an adult population; it is therefore important to identify risk factors for shoulder pain onset in order to control them. Previous studies have analysed factors such as strength and shoulder RoM, however, these studies were only performed on a population of young athletes (10-17 years) (Silva et al., 2006) or amateur female tennis players (Stanley et al., 2004). To the best of the authors' knowledge an adult population of master tennis athletes (aged >40 years) has not been studied yet.

Hence, the objective of this study was to compare strength, RoM, and SHR in the dominant (DS) and non-dominant (NDS) shoulder between a cohort of master tennis athletes and an age-matched group of non-tennis athletes (controls). We hypothesized that master tennis players would have exhibited specific patterns of strength (i.e., imbalance or weakness of rotator cuff muscles), RoM (i.e., internal rotation deficit), and SHR (i.e., deviation from physiological value) in their DS compared to non-tennis athletes. Alterations in shoulder biomechanics, if confirmed, could potentially contribute to a higher risk of shoulder injuries in the master tennis player population.

METHODS

Participants and study design

This study was a two-group comparative cross-sectional study. The enrolment of the participants took place through word of mouth within tennis sports centres near the Rehabilitation Centre of Campus Bio-Medico University Hospital Foundation and the "*Foro Italico*" University Foundation. The main inclusion criteria were age >40 years, at least 5 years of sport practice, at least 4.5 hours per week of training/competitions. All participants suffering from disorders that could hinder the correct execution of the assessment protocol (i.e. recent shoulder fracture, neurological and cognitive problems) were excluded.

The study received the approval by the Ethical Committee of Campus Bio-Medico University (Prot. PAR 001.22(62.21)) and was carried out according to the Declaration of Helsinki Ethical Principles. All participants signed the informed consent before data collection.

A total sample of 15 male master tennis athletes (TA), and 15 male non-tennis athletes (CTRL) participated in the study. Descriptive characteristics of the participants are reported in Table 1. Tennis athletes had been playing for an average of 42 years and usually played tennis an average of 10 hours per week. All participants stated that they usually performed a single-handed backhand stroke. Non-tennis athletes had been playing for an average of 23 years and were playing on average 7 hours per week. The type of sport practiced by the CTRL were as follows: swimming (33%), athletics/running (27%), cycling (12%), soccer (7%), aerobics (7%), basketball (7%), kite surfing (7%).

Table 1. Participant demographics.

Variable	Tennis Athletes (n = 15)	Non-Tennis Athletes (n = 15)
Age [years]	57 ± 9[1]	54 ± 6[1]
Starting age [years]	15 ± 11[1]	29 ± 13[1]
Years of play [years]	42 ± 13[1]	25 ± 13[1]
Hours per week (training plus competition) [hours]	10.2 ± 9.4[1]	6.9 ± 4.3[1]
Right-hand play (dominant) [%]	86.6	86.6
Single-handed backhand [%]	100	-
History of dominant shoulder pain [n]	5	4
Constant-Murley score (dominant shoulder)	96.9 ± 6.7[1]	95.6 ± 4.9[1]
Constant-Murley score (non-dominant shoulder)	99.0 ± 2.6[1]	96.7 ± 4.0
Height [m]	1.78 ± 0.08[1]	1.75 ± 0.08[1]
Body Mass [kg]	79.7 ± 8.6[1]	77.4 ± 12.5[1]
BMI [kg/m^2]	25.2 ± 2.6[1]	25.1 ± 3.1[1]

Note. [1]Values are expressed as mean ± standard deviation.

Procedures and measures

Strength assessment

Shoulder strength assessments were performed by one physiotherapist only by means of maximum voluntary isometric contraction (MVIC) during several tasks involving: shoulder flexion, extension, abduction, adduction, internal and external rotation. The Chronojump Force Sensor Kit (Boscosystem®, Barcelona, Spain), which was connected to a position-adjustable single-pulley cable system, was used to record MVIC as detailed in a previous study (Bravi et al., 2023). The use of the fixed dynamometer was preferred over the hand-held because it shows higher reliability values (Beshay et al., 2010).

All participants performed the isometric tests in a standing position, with the upper limbs positioned as follows:

- The assessments of shoulder flexion and extension strength, in the sagittal plane, were performed with the shoulder at a 90° angle of flexion, the elbow fully extended, and the forearm held in an intermediate position between pronation and supination (i.e. with the thumb pointing up).
- The assessments of shoulder abduction and adduction strength, in the frontal plane, were performed with the shoulder at a 90° angle of abduction, the elbow fully extended, and the forearm positioned in an intermediate position between pronation and supination (i.e. with the thumb pointing up).
- The assessments of shoulder internal (IR) and external rotation (ER) strength were performed with the shoulder in adduction, and the elbow flexed at 90°. Participants were instructed to maintain their elbows close to their sides throughout the test.

Participants were instructed to increase their force gradually to a maximum effort in 2 seconds, maintain it for 5 seconds, and then return to the rest position. The analysis was performed on the mean 3 seconds of maximal contraction for each trial and the peak force was selected, Finally, peak force was averaged in the 3 test trials and normalized to body mass. The external rotation to internal rotation ratio (ER/IR) was calculated from the mean value that was recorded during the assessments of ER and IR.

Range of motion
A physiotherapist assessed active and passive RoM of the shoulder using a goniometer. The RoM assessment took place with the patient seated, their arm abducted at a 90° angle, and their elbow flexed at 90°. The goniometer's axis was aligned with the olecranon process of the ulna, the stationary arm was positioned vertically, perpendicular to the floor, and the moving arm was extended from the axis point to the ulnar styloid process on the forearm's ulnar side.

Scapulohumeral rhythm
The SHR was assessed using 4 wearable inertial sensors-based three-dimensional (3D) orientation trackers (Xsens DOT, Xsens Tecnologies B.V, Enschede, The Netherlands) according to the ISEO protocol as described in Cutti et al. (Cutti et al., 2008). Briefly, the ISEO protocol suggests that sensors should be positioned on the thorax, scapula, upper arm and forearm (Figure 1A), and that a functional calibration procedure should be carried out to relate the orientation of the sensor to that of the underlying bony segment. The functional calibration consisted of two phases: (1) a 10-second recording phase of static positions, during which participants were instructed to maintain their arm adducted alongside the body, with the elbow flexed at 90°, and the forearm in a neutral position between pronation and supination (with the palm facing medially); and (2) an additional 10-second recording phase during which participants performed five consecutive pronation-supination movements of the forearm.

After sensors positioning and the functional calibration, participants were asked to perform 5 repetitions of shoulder flexion in the sagittal plane, shoulder abduction (frontal plane flexion) and shoulder flexion in the scapular plane (i.e. shoulder scaption) with (i.e. loaded tasks) and without (i.e. unloaded tasks) holding the 2kg dumbbells (Figure 1B). Participants were instructed to reach maximum shoulder flexion in 3 seconds and to return to the initial resting position in 3 seconds. In total 30 repetitions were recorded for each participant.

The same order of limb assessment (dominant, then non-dominant) was used for all participants. The choice of weight was made in accordance with the findings of the previous study by McClure et al. (2009) who showed how athletes, including those with mild to moderate shoulder symptoms, are able of lifting such weight through the full range of motion repetitively.

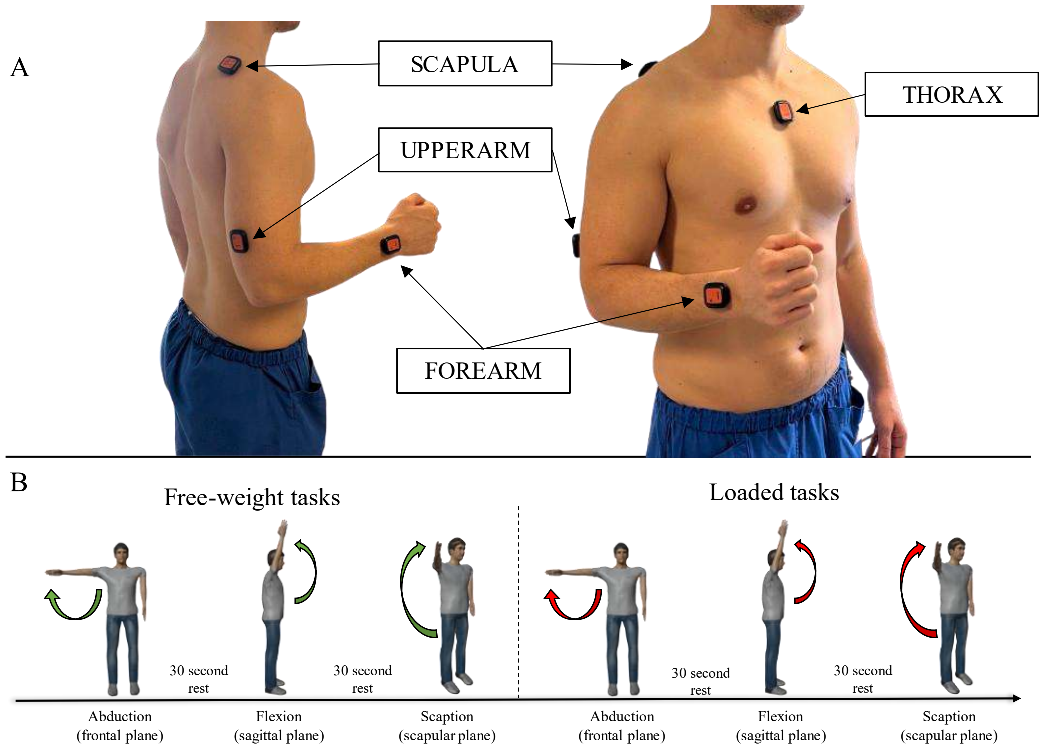

Figure 1. A. Xsens DOT sensor placement. One sensor placed at the level of the sternum (referred to as thorax), one sensor placed superior to the midpoint of the scapular spine (referred to as scapula), one sensor placed on the posterior aspect of the distal humerus (referred to as upper arm), and one sensor placed distally on the anterior aspect of the forearm (referred to as forearm). B. Schematic representation of the tasks performed for the assessment of scapulohumeral rhythm. All participants first executed 5 repetitions of unloaded movements, followed by 5 repetitions using a 2kg dumbbell for each shoulder flexion movement in the frontal, sagittal, and scapular planes. The images of schematic representations were created with Blender 3.6.5 - a 3D modelling and rendering package, Stichting Blender Foundation, Amsterdam and MakeHuman 1.2.0 opensource tool.

The recorded data were subsequently extracted and analysed using a custom algorithm that was implemented in MATLAB R2020b (The MathWorks Inc., Natick, Massachusetts, USA). In particular: a) thorax, scapula, upper arm and forearm axes orientation were determined as suggested by Cutti et al. (Cutti et al., 2008) from sensors data recorded during the functional calibration; b) humeral elevation (H) and scapular medio-lateral rotation (S) were computed according to Wu et al. (Wu et al., 2005) from sensors data recorded during the loaded and unloaded tasks; c) SHR was, then, computed as suggested by Lee et al. (K. W. Lee et al., 2016; S. K. Lee et al., 2013) at 10° intervals of arm elevation during both the ascending and descending phase of each task, with the following formula:

$$SHR = \frac{H - S}{S}$$

For each task, the mean value of the 5 repetitions was then used for the analysis.

Analysis

Data were analysed using IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA). Descriptive analysis including mean and standard deviation of all variables that were computed. Since not all the variables were normally distributed, the non-parametric paired samples Wilcoxon test (statistical significance was set at $p < .05$) was used to compare the strength, RoM and SHR between the DS and the non-dominant shoulder (NDS); the Mann-Whitney U Test was used to compare data between tennis athletes and controls.

RESULTS

The evaluation of both passive and active shoulder external rotation RoM showed that DS of TG was significantly higher than NDS (passive RoM: DS = 93.1 ± 3.7°, NDS = 90.7 ± 6.9°, $p = .024$; active RoM: DS = 86.1 ± 7.1°, NDS = 83.8 ± 9.9°, $p = .009$). The CTRL group showed no significant differences between DS and NDS. The comparison of TG and CTRL showed no significant differences in both passive and active RoM. All other values are reported in Table 2.

Strength assessment of TG showed significantly higher values in DS than NDS for the extension (DS = 3.12 ± 0.55 N/kg, NDS = 2.84 ± 0.51 N/kg, $p = .001$) and for the adduction assessment (DS = 2.85 ± 0.48 N/kg, NDS = 2.59 ± 0.45 N/kg, $p = .004$). CTRL showed significant higher values in DS with respect to NDS for shoulder extension (DS = 2.51 ± 0.79 N/kg, NDS = 2.41 ± 0.69 N/kg, $p = .033$). The comparison between TG and CTRL showed significant higher strength in DS of TG for shoulder extension (TG = 3.12 ± 0.55 N/kg, CTRL = 2.51 ± 0.79 N/kg, $p = .024$), shoulder abduction (TG = 1.62 ± 0.41 N/kg, CTRL = 1.30 ± 0.31 N/kg, $p = .026$), shoulder adduction (TG = 2.85 ± 0.48 N/kg, CTRL = 2.33 ± 0.65 N/kg, $p = .018$) and shoulder external rotation (TG = 1.74 ± 0.41 N/kg, CTRL = 1.43 ± 0.32 N/kg, $p = .046$); The NDS showed only significant higher external rotation strength of TG respect to CTRL (TG = 1.66 ± 0.44 N/kg, CTRL = 1.33 ± 0.21 N/kg, $p = .034$). All the other assessment, including the external to internal rotator strength ratio (ER/IR ratio), showed no significant differences (Table 2).

The SHR of the TG exhibited significantly lower values for the DS in all three planes of motion during both the weight-free assessments (without holding the 2kg dumbbells) and the weighted assessments (holding the 2kg dumbbells) when compared to the NDS (weight-free tests: frontal $p = .004$, sagittal $p = .003$, scapular $p = .001$; weighted tests: frontal $p = .004$, sagittal $p = .001$, scapular $p = .001$). In Table 3 all the DS and NDS SHR values are reported.

The comparison of SHR between the unloaded and loaded tasks revealed distinct patterns. Specifically, there was a significant reduction in DS for the TG during loaded tests (abduction unloaded = 2.33 ± 0.84, loaded = 2.19 ± 0.81, $p = .005$; flexion unloaded = 2.47 ± 0.73, loaded = 2.30 ± 0.79, $p = .010$; scaption unloaded = 2.43 ± 0.72, loaded 2.19 ± 0.77, $p = .003$). When examining the NDS results, a similar trend was identified with lower values during loaded tasks. However, this difference reached statistical significance only in the case of shoulder flexion on the frontal plane (unloaded = 3.33 ± 1.59, loaded = 2.93 ± 1.0o1, $p = .017$). The CTRL group showed no significant differences in DS while significant reductions of SHR during loaded tasks were observed in NDS during shoulder abduction and scaption movements, as indicated in Table 3.

The comparison between TG and CTRL showed no significant differences during both the unloaded and loaded tasks (Table 3). Finally, the NDS of TG showed significantly higher SHR values in all tasks, with a similar trend in the control group (Table 3). Figure 2 graphically summarizes the SHR values.

Table 2. Comparison within and between groups of shoulder range of motion and strength.

	Tennis Players		**Controls**		**Tennis Player**			**Controls**			**Tennis Player vs Controls**					
					Dominant vs Non-Dominant			**Dominant vs Non-Dominant**			**Dominant**			**Non-Dominant**		
	Dominant[1]	**Non-Dominant[1]**	**Dominant [1]**	**Non-Dominant[1]**	***p*-value**	**Z**	**MD**	***p*-value**	**Z**	**MD**	***p*-value**	**Z**	**MD**	***p*-value**	**Z**	**MD**
Constant-Murley Score	96 ± 6.7	98 ± 3.1	96 ± 4.8	97 ± 4.0	.72	-1.802	-2.00	.121	-1.552	-1.00	.050	-1.956	0.0	**.012**	-2.519	1.00
Passive ROM																
Flexion [°]	179.2 ± 2.6	177.2 ± 6.8	178.9 ± 2.9	178.8 ± 3.2	.109	-1.604	1.76	.655	-0.447	0.10	.972	-0.035	0.40	.609	-0.511	-1.30
Abduction [°]	179.0 ± 2.8	178.8 ± 3.2	178.8 ± 3.2	178.7 ± 3.5	1.000	-0.272	0.17	.317	-1.000	0.10	.972	-0.035	0.30	.944	-0.070	0.20
External rotation [°]	93.1 ± 3.7	90.7 ± 6.9	93.1 ± 6.9	91.7 ± 8.7	**.024**	-2.264	2.94	.089	-1.702	1.40	.465	-0.731	0.30	.983	-0.021	-1.20
Internal rotation [°]	82.0 ± 5.9	83.1 ± 6.9	85.0 ± 6.1	84.9 ± 8.4	.727	-0.350	-0.17	1.000	0.000	0.10	.134	-1.497	-2.40	.346	-0.942	-2.10
Active ROM																
Flexion [°]	176.5 ± 5.1	175.8 ± 7.8	174.7 ± 5.7	174.3 ± 5.7	.854	-0.184	0.58	.500	-0.674	0.40	.245	-1.163	1.90	.221	-1.225	1.70
Abduction [°]	177.5 ± 4.8	177.1 ± 6.5	174.6 ± 5.2	174.3 ± 5.5	.465	-0.730	0.64	.715	-0.365	0.30	.064	-1.852	3.20	.077	-1.767	2.80
External rotation [°]	86.1 ± 7.1	83.8 ± 9.9	87.5 ± 9.0	86.4 ± 11.3	**.009**	-2.621	3.00	.503	-0.669	1.10	.770	-0.292	-1.00	.336	-0.962	-2.90
Internal rotation [°]	74.7 ± 6.9	75.9 ± 8.1	78.7 ± 7.6	79.5 ± 11.8	.687	-0.403	-0.52	.455	-0.747	-0.80	.058	-1.895	-3.80	.100	-1.644	-4.00
Shoulder strength test																
Flexion [N/kg]	1.69 ± 0.46	1.66 ± 0.38	1.43 ± 0.37	1.40 ± 0.31	.227	-1.207	0.04	.394	-0.852	0.03	.059	-1.887	0.21	.059	-1.888	0.20
Extension [N/kg]	3.12 ± 0.55	2.84 ± 0.51	2.51 ± 0.79	2.41 ± 0.69	**.001**	-3.385	0.28	**.033**	-2.131	0.10	**.024**	-2.261	0.52	.071	-1.804	0.34
Abduction [N/kg]	1.62 ± 0.41	1.54 ± 0.39	1.30 ± 0.31	1.28 ± 0.27	.068	-1.823	0.08	.551	-0.597	0.02	**.026**	-2.220	0.28	.056	-1.909	0.22
Adduction [N/kg]	2.85 ± 0.48	2.59 ± 0.45	2.33 ± 0.65	2.27 ± 0.64	**.004**	-2.864	0.24	.140	-1.477	0.06	**.018**	-2.365	0.44	.141	-1.472	0.26
Internal rotation [N/kg]	2.17 ± 0.46	2.19 ± 0.55	1.91 ± 0.46	1.94 ± 0.43	.554	-0.592	-0.03	.315	-1.005	-0.03	.141	-1.473	0.23	.184	-1.328	0.23
External rotation [N/kg]	1.74 ± 0.41	1.66 ± 0.44	1.43 ± 0.32	1.33 ± 0.21	.332	-0.970	0.08	.105	-1.32.	0.10	**.046**	-1.992	0.23	**.034**	-2.116	0.25
ER/IR [ratio]	0.81 ± 0.15	0.77 ± 0.14	0.76 ± 0.11	0.70 ± 0.11	.287	-1.065	0.04	.061	-1.874	0.06	.319	-0.431	0.02	.184	-1.329	0.04

Note. [1]Values are expressed as mean ± standard deviation. The comparisons show p values, mean differences and Z value. Bold indicates statistically significant differences (p < .05). MD = mean difference.

Table 3. Comparison within and between groups of scapulohumeral rhythm.

	Tennis Players		**Controls**		**Tennis Player**			**Controls**			**Tennis Player vs Controls**					
					Dominant vs Non-Dominant			**Dominant vs Non-Dominant**			**Dominant**			**Non-Dominant**		
	Dominant[1]	**Non-Dominant[1]**	**Dominant [1]**	**Non-Dominant[1]**	***p*-value**	**Z**	**MD**	***p*-value**	**Z**	**MD**	***p*-value**	**Z**	**MD**	***p*-value**	**Z**	**MD**
Abduction (frontal plane)																
Unloaded [ratio]	2.33 ± 0.84	3.33 ± 1.59	2.30 ± 0.55	3.21 ± 0.92	**.004**	-2.911	-0.98	**.005**	-2.784	-0.91	.836	-0.207	0.03	.619	-0.498	0.10
Loaded [ratio]	2.19 ± 0.81	2.93 ± 1.01	2.13 ± 0.38	2.92 ± 0.75	**.006**	-2.769	-0.76	**.002**	-3.067	-0.79	.575	-0.560	0.17	.836	-0.207	0.29
p-value	**.005**	**.017**	.094	**.025**												
Z	-2.841	-2.391	-1.676	-2.244												
Mean difference	0.15	0.28	0.17	0.29												
Flexion (sagittal plane)																
Unloaded [ratio]	2.47 ± 0.73	3.69 ± 1.13	2.59 ± 0.51	3.62 ± 0.94	**.003**	-2.959	-1.23	**.002**	-3.124	-1.03	.430	-0.788	-0.12	.756	-0.311	0.08
Loaded [ratio]	2.30 ± 0.79	3.42 ± 0.81	2.61 ± 0.71	3.32 ± 1.18	**.001**	-3.195	-1.15	.112	-1.590	-0.71	.213	-1.244	-0.35	.507	-0.664	0.10
p-value	**.010**	.124	.865	.074												
Z	-2.585	-1.538	-0.170	-1.789												
Mean difference	0.21	0.28	-0.02	0.30												
Scaption (scapular plane)																
Unloaded [ratio]	2.43 ± 0.72	3.62 ± 1.33	2.42 ± 0.72	3.41 ± 0.82	**.001**	-3.243	-1.15	**.002**	-3.124	-0.99	.740	-0.332	0.01	.694	-0.394	-0.99
Loaded [ratio]	2.19 ± 0.77	3.32 ± 0.78	2.39 ± 0.66	2.90 ± 0.71	**.001**	-3.290	-1.15	**.047**	-1.989	-0.51	.694	-1.100	-0.22	.229	-1.203	-0.51
p-value	**.003**	.076	.629	**.002**												
Z	-2.959	-1.775	-0.483	-3.068												
Mean difference	0.26	0.26	0.03	0.51												

Note. [1]Values are expressed as mean ± standard deviation. The comparisons show p values, mean differences and Z value. Bold indicates statistically significant differences (p < .05). MD = mean difference.

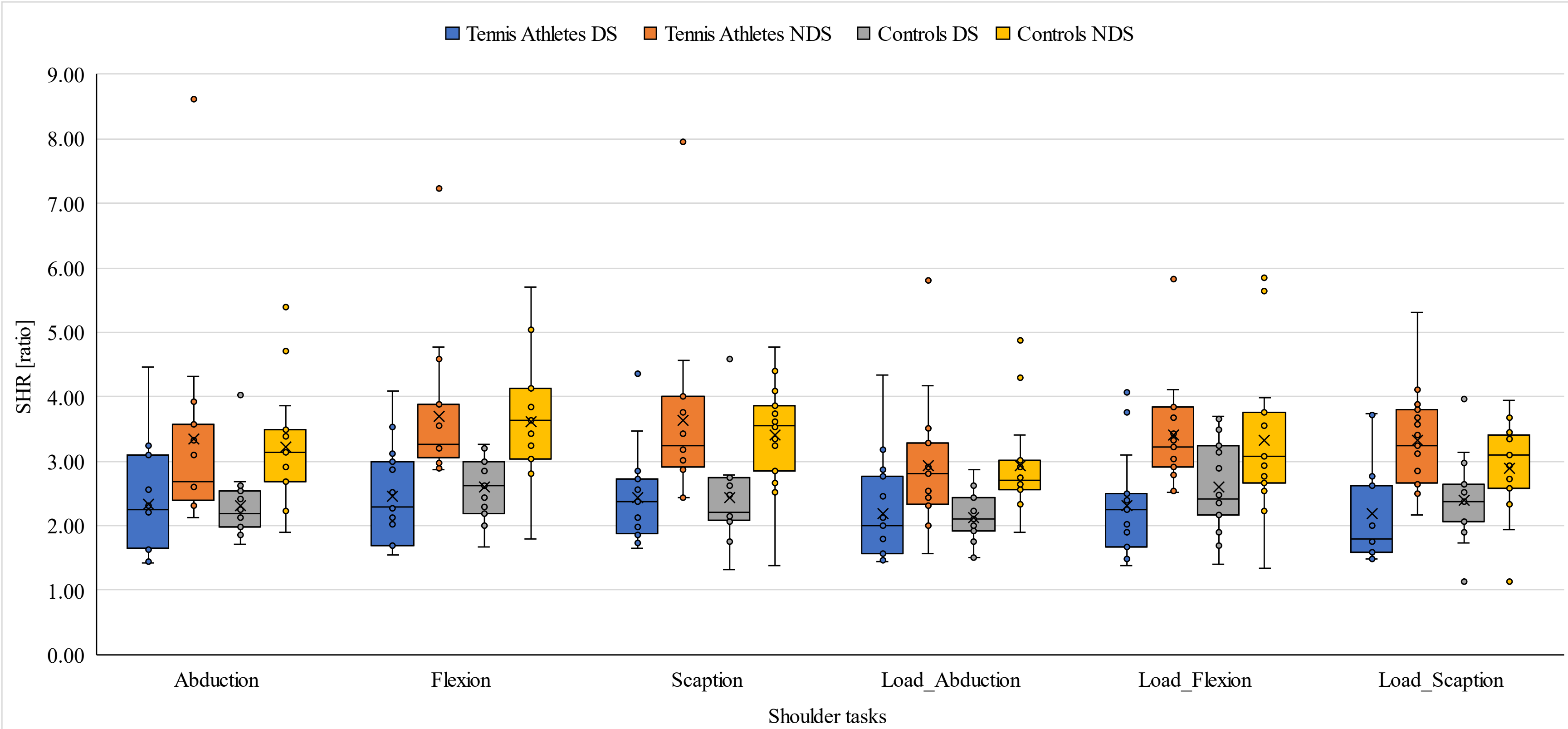

Figure 2. Scapulohumeral rhythm (SHR) during unloaded and loaded shoulder abduction (frontal plane), flexion (sagittal plane) and scaption (scapular plane).

DISCUSSION

The main finding of this study was that master tennis athletes showed higher strength in the dominant shoulder than non-tennis athletes, with no differences in shoulder RoM and SHR characteristics. Therefore, tennis practice in older age does not appear to affect the main biomechanical factors that are related to shoulder injuries.

DS of master tennis athletes had significantly higher external rotation RoM than the non-dominant shoulder (NDS). This aligns with previous studies (W. Ben Kibler et al., 1996b; Schmidt-Wiethoff et al., 2004), which reported that tennis players often exhibit an increased external rotation in their DS due to the repetitive overhead movements that are executed during tennis strokes. This has been commonly considered as a sport-specific adaptation that occurs particularly in highly trained tennis players (Ellenbeckert, 1992; W. Ben Kibler et al., 1996b). The study by Schmidt-Wiethoff et al. (2004) compared shoulder RoM between the DS and NDS in professional male tennis players and reported an increased RoM of external rotation in the DS. However, it is important to note that shoulder RoM differences between the DS and NDS have been the focus of several research studies (Cools et al., 2014; W. Ben Kibler et al., 1996a; Schmidt-Wiethoff et al., 2004; Stanley et al., 2004) and the scientific evidence in this regard is still conflicting. In contrast to studies which found an increase in external rotation RoM of DS, Ellenbecker et al. (1996) did not find an increase in external rotation RoM in the DS, but a significant reduction in internal rotation RoM in a population of male and female elite junior tennis players. Furthermore, the study by Stanley et al. (Stanley et al., 2004), that was performed on female amateur tennis players, revealed no differences in RoM. The variability of these findings could be attributed to variations in age, skill level, and training frequency, suggesting that shoulder adaptations may evolve over time with long-term tennis participation.

Interestingly, our study revealed no significant differences in either passive or active RoM when comparing the tennis athletes (TG) to the control group (CTRL). This finding suggests that, despite the long-term engagement in tennis, master athletes do not show alterations in shoulder RoM when compared to an age-matched group of non-tennis athletes.

These findings, obtained from a cohort of male athletes over 40 years old, differ from those of Schmidt-Wiethoff et al. (2004) who reported a significant reduction in total rotational RoM in the DS of younger tennis athletes compared to a control group that did engage in overhead sports. Similarly, studies by Kibler et al. (1996b) on elite tennis players with an average age of 18 years, and by Cools et al. (2014) on elite adolescent tennis players, found a reduction in internal shoulder rotation RoM. One possible explanation for these contrasting results could be the differences in age, skill level, and weekly training exposure of the populations analysed in these previous studies compared to the master athletes participating in the present study. Moreover, these conflicting results may be attributed to differences in the methods used for RoM assessment. In the present study, RoM was evaluated in a sitting position, similar to the study by Stanley et al. (2004), which could enhance scapulothoracic movement. In contrast, other studies (Cools et al., 2014; Kibler et al., 1996a) used the supine position, in which the weight of the trunk on a hard surface reduces compensatory scapular movements. Therefore, the differences in methodologies across studies might account for the variability in reported shoulder RoM adaptations.

Regarding shoulder strength, our tennis athletes exhibited significantly higher values in their DS for extension and adduction compared to the NDS. Additionally, the master tennis athletes showed greater strength in the DS for extension, abduction, adduction, and external rotation when compared to the CTRL. In contrast to Cools et al. (2014), who found higher external rotation strength in adolescent tennis athletes, the present study did not exhibit a significant difference in external rotation strength between the DS and NDS in master athletes. Instead, the differences in strength were mainly observed in extension and adduction in the athletes participating in our study. Two considerations are necessary to explain these findings. Firstly, directly comparing our findings with the existing literature is challenging due to considerable variability in assessment methods across studies, including differences in limb positioning and the instruments used (e.g., handheld vs. fixed dynamometers, isokinetic systems). For example, Cools et al. (2014) used a handheld dynamometer with participants tested in supine position, while our study employed a fixed dynamometer, with participant in upright position, to ensure greater measurement reliability. The second consideration concerns the age of the population and the exposure to sports practice. In the study by Cools et al. (2014), the participants were adolescents with a training exposure reaching 15.6 hours per week, whereas our population of master tennis athletes had an average exposure of 10 hours per week. It is therefore plausible that the differences in strength are related to the potential impact of repetitive, high-load overhead movements in tennis, which may lead to specific strength adaptations, particularly in the rotator muscles. Hence, the higher number of practice hours and the younger age of the participants in previous studies could explain this difference.

However, while increased strength is generally considered beneficial for athletic performance, it is crucial to maintain a balanced ratio between internal and external rotator strength (ER/IR ratio) to reduce the risk of overuse injuries (Byram et al., 2010; Codine et al., 1997; T. Ellenbecker & Roetert, 2003). In our study, we observed no significant differences in ER/IR strength ratios between the DS and NDS in tennis players or between tennis athletes and controls. This contrasts with findings from studies on younger athletes, such as Cools et al. (2014), who investigated a population of young tennis players and reported ER/IR ratios ranging from 66.2% for the DS to 74.3% for the NDS. In our study, the ER/IR ratio was approximately 80%, aligning with data from Bradley and Pierpoint (2023), who reported ratios ranging from 71% to 86% in a healthy active population. This indicates a favourable balance between the strength of internal and external rotator muscles, suggesting that rotator cuff muscles have the capacity to effectively maintain dynamic shoulder stabilization (Bradley & Pierpoint, 2023). The maintenance of a balanced ER/IR ratio in our master tennis athletes could indicate that they either have developed protective adaptations over time.

The assessment of SHR, an indicator of scapular dyskinesis, for injury risk prevention remains a subject of debate in literature. In the 2022 Bern Consensus Statement (Schwank et al., 2022), approximately half of the Delphi group recommended screening for scapular dyskinesis, while the other half opposed it. Meanwhile, some authors consider it an essential aspect to evaluate (Kibler et al., 2012; Scibek & Carcia, 2012) as the coordinated movement of the scapula and the humerus is pivotal for the normal function of the shoulder (Kibler, 1998). Therefore, monitoring SHR (to estimate the scapula and humerus coordinated motion) could be a key aspect when dealing with overhead athletes (Scibek & Carcia, 2012).

Our results revealed that tennis athletes exhibited significantly lower SHR values in their DS compared to the NDS, both during unloaded and loaded tasks, in agreement with the findings of Hosseinimehr et al. (2015) who indicated that DS of overhead athletes (handball and volleyball athletes) exhibited lower SHR values than NDS. Moreover, our findings reveal no significant differences between master tennis athletes and controls, in line with the results of Pascoal et al. (2023), in which a similar comparison between overhead athletes (30-year-old volleyball players) and non-overhead athletes was carried out. In the present study, TG showed SHR values in the DS that approached 2:1, which has been normally defined as a physiological measure (Inman et al., 1996). However, the higher SHR values observed in the NDS should not raise concern since this parameter can vary in the healthy subject between 1.1:1 and 3.5:1, as shown in literature (Forte et al., 2009; Hosseinimehr et al., 2015; Scibek & Carcia, 2012; Yano et al., 2010), and a similar trend was confirmed in control group. Furthermore, scapular motion asymmetries, as those that emerged in the present study, may be common in overhead athletes. Nevertheless, these asymmetries should not be considered as a pathological sign but rather an adaptation to the sporting gesture (Hosseinimehr et al., 2015; Pascoal et al., 2023).

The results of our study indicated that during the loaded tasks master tennis athletes exhibited significantly lower SHR values on their DS, approaching the physiological ratio of 2:1. In contrast, a different pattern was observed in the CTRL. Minimal, non-significant decreases in SHR were found between the loaded and unloaded tasks in the DS across all movements, except for flexion in the sagittal plane, whereas non-significant greater values were found during the loaded task.

A potential explanation for this result could be that tennis players during sporting gestures are subject to rapid acceleration/deceleration movements of the arm that require strong muscular activation and fine motor control. This is particularly evident during the serve, which is recognized as the most demanding stroke on the upper extremity (Alrabaa et al., 2020). During the acceleration phase of the serve, an explosive contraction of the internal rotator muscles, with the shoulder in abduction and external rotation, generates an average angular velocity of about 2420°/s (Elliott, 2006; Fleisig et al., 2003; Johnson & McHugh, 2006). Furthermore, it has been demonstrated that the racket can influence joint power, as indicated by Creveaux et al. (2013). Their research showed that serving with a lighter racket led to greater shoulder internal moments compared to using a heavier one, even with similar performance (i.e. post-impact ball velocity). The authors suggested that this could be due to insufficient activation of the latissimus dorsi muscle, which normally resists humeral distraction during overhead movements. As a result, there may be a compensatory increase in the activity of certain rotator cuff muscles to stabilize the shoulder and maintain control during the serve. This could justify the fact that the weighted task induced a similar motor control, as exhibited in the present study and generally reported during sport specific gestures, resulting in a greater regulation of the SHR.

From a clinical standpoint to the best of our knowledge, this is the first study implementing a normative reference dataset, which provides important perspectives for the clinical evaluation of shoulder function in master tennis athletes, with a specific focus on the scapulothoracic joint. Our results suggest that master tennis athletes exhibit a typical variability in the SHR of their DS during arm elevation. These findings can be used in conjunction with other clinical criteria to delineate a reference point, aiding clinicians in the management of shoulder injuries of master tennis athletes: from diagnosis, through development of rehabilitation strategies, and, finally, to informed decision-making when assessing an athlete's readiness to return to play. We believe that rehabilitation professionals can use these data to guide assessment and develop targeted conditioning programs aimed at maintaining shoulder health. For instance, the relatively balanced ER/IR strength ratio observed in our cohort suggests that strength training programs for master tennis athletes should continue to emphasize both internal and external rotator muscles to preserve shoulder stability.

Some limitations of the present study need to be addressed. First, the population of our study includes only male subjects, future studies should include larger cohorts of both male and female athletes to capture a more comprehensive picture of shoulder adaptations in master tennis players. Second, the cross-sectional design of this study limits our ability to detect a causal relationship between the observed shoulder adaptations and the risk of injury. Therefore, longitudinal studies are needed to determine how these biomechanical characteristics evolve over time and whether they contribute to injury occurrence. Third, while this study assessed SHR using inertial sensors, it did not measure muscle activation patterns. Incorporating electromyography (EMG) in future research would provide a more detailed understanding of the neuromuscular control involved in shoulder movements. Finally, we only included master athletes with a long history of tennis participation. Investigating different levels of play and different training volumes could help identify how specific training regimens impact shoulder biomechanics in master athletes.

CONCLUSION

The findings of the present study suggest that long-term participation in tennis during adulthood does not affect the main biomechanical factors that are typically associated to the risk of shoulder injuries. Although tennis participation seems to enhance strength in the dominant shoulder, it does not appear to cause significant alterations in the range of motion when compared to non-tennis athletes. Additionally, SHR values were similar between master tennis athletes and controls, with the dominant side in both groups close to the physiological ratio of 2:1.

These findings provide a reference point for rehabilitation professionals working with master tennis athletes and can assist clinicians and coaches in developing targeted training and rehabilitation strategies to preserve shoulder function and to support a prolonged tennis participation. Finally, this study contributes to establishing an initial normative reference dataset for evaluating shoulder biomechanics in male master tennis athletes, with a specific focus on the scapulothoracic joint, including range of motion, strength, and scapulohumeral rhythm.

AUTHOR CONTRIBUTIONS

The study was conceptualized by Marco Bravi, Chiara Fossati, Fabio Pigozzi, and Andrea Macaluso. The methodology was developed by Marco Bravi, Chiara Fossati, Arrigo Giombini, Andrea Macaluso, Riccardo Borzuola, Giuseppe Vannozzi, and Pietro Picerno. Data curation was carried out by Marco Bravi, Riccardo Borzuola and Fabio Santacaterina. Marco Bravi, Riccardo Borzuola, and Chiara Fossati prepared the original draft, while Arrigo Giombini, Giuseppe Massazza, Ugo Riba and Andrea Macaluso contributed to the review and editing of the manuscript. Supervision was provided by Chiara Fossati, Fabio Pigozzi, Andrea Macaluso, and Rocco Papalia. All authors have read and approved the final version of the manuscript.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Validation of the questionnaire Conditions of Effective Gender Equality in Sport

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ABSTRACT

Gender equality is a fundamental right for all people, achieved by respecting the principles of equal opportunities and non-discrimination. Analysing the existence of this equality by carrying out studies that present a gender perspective is essential to be able to contribute to the sustainable development of the different sectors existing in society, such as sport. Thus, the main objective is to design and validate a quantitative tool to analyse the existence of effective gender equality in sport. First, a group of experts analysed the design of the questionnaire. Then, a first pilot test was carried out with an exclusive sample of women, where no reliable results were presented. Subsequently, the questionnaire was distributed to both women and men at the Pan American Games in Chile in 2023. The results obtained from the Exploratory Factor Analysis, the Confirmatory Factor Analysis and the Reliability calculation were favourable and optimal, thus confirming that the questionnaire is valid and reliable for the analysis of effective equality. The final structure presents a total of 16 items divided into the dimensions of Sport Growth, Material Barriers and Empowerment.
Keywords: Gender equity, Parity, Equal treatment, Real equality, Formal equality.

Cite this article as:
Carboneros, M., López-Gullón, J. M., & Angosto, S. (2025). Validation of the questionnaire Conditions of Effective Gender Equality in Sport. *Journal of Human Sport and Exercise, 20*(2), 515-532. https://doi.org/10.55860/9g6hv856

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Submitted for publication September 10, 2024.
Accepted for publication October 29, 2024.
Published February 10, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/9g6hv856

INTRODUCTION

Achieving effective equality between men and women is a global challenge facing all countries today in order to build a peaceful, prosperous and sustainable society (UN, 2020). The creation of new policies and changes to existing legislation are key factors in achieving this gender equality (Alves da Silva, 2024; Pastor and Acosta, 2016). This legislative equality, related to the existence of equal opportunities and non-discrimination between women and men before the law, is called formal gender equality (Sierra, 2018). Currently, although there are laws that guarantee this type of equality, there continues to be significant discrimination in various sectors of society, which makes it impossible to transform formal gender equality into real or effective gender equality. Many individuals who do not conform to traditional gender roles and expectations still suffer prejudice and social discrimination (Lee and Cunninham, 2016). Some examples are related to the reduction of opportunities for women (UN Women, 2022), the devaluation of paid jobs (González et al., 2019) or the lack of accessibility in leadership positions (Powell, 2018).

Today's society must be sensitive and responsible to these situations, seeking a significant change that breaks the separation of traditional gender roles that continue to exist within social norms, values and beliefs in many contexts (Alberdi et al., 2024; Trolan, 2013). Within this society, sport is an important socio-cultural phenomenon that acts as an engine of change to achieve gender equality. Sport is a transmitter of values such as solidarity, respect and inclusion, catering to a sporting cultural reality where all genders can thrive on equal terms (Harmon, 2020); furthermore, the practice of sport is inherent to any condition, role or ability (Nordstrom et al., 2016). Sport as sexual integration challenges gender stereotypes (UN Women, 2022) and helps to situate both genders in mutually respectful relationships, rejecting any conventional sexualised forms (Maclean, 2015). Despite this, women continue to experience significant barriers and differences compared to men that prevent the existence of effective equality (Barreira and Da Silva, 2016; Pill et al., 2024).

Looking at specific aspects related to barriers to effective equality, a lack of social valuation of women's sport can be identified, with the existence of numerous sexist stereotypes (Hoeber 2008; Kavourda et al., 2018; Klavanes et al., 2020; Mérida et al., 2022; Volta et al., 2019). For example, women's perceived poor leadership and low belief in their abilities hinder access to high-level sport positions (Blom et al., 2011; Lee et al., 2017). Also, the resources allocated in sport are often not equally distributed between women and men (Hoeber, 2008), such as the lack of quality and scarcity of material resources, poor sport schedules, equipment and infrastructure (Doğusan and Kiçak 2021; McGinnis et al., 2005) and the scarcity of financial resources and sponsorship (Kamphoff, 2010; O'Brien et al., 2023; Norman and Simpson, 2022).

On the other hand, although female participation has increased in different sporting positions, their responsibilities are still restricted to positions of lesser relevance (Passero et al., 2019). The existence of women in high leadership positions is scarce, worldwide, (Donoso et al., 2023), not only in sports entities, but also in elite coaching or refereeing positions, among other positions (Klavanes et al. (2020); Tjønndal, 2019; Knoppers et al., 2022; Winiarska et al., 2016). Thus, low salaries predominate due to the presence of women in less important positions, with a less decisive division of tasks assigned, fulfilling gender stereotypes in society (Cepeda, 2021; Claringbould and Knoppers, 2012; O' Brien et al., 2023). It should be noted that these women in leadership positions, including sportswomen, have to reconcile their sporting life with their family life. Some favourable measures are related to family co-responsibility policies that prevent women from abandoning their sporting careers (Claringbould and Knoppers, 2012; Klavanes et al., 2020; Organista, 2020), or the existence of aid or action plans that favour the sporting reincorporation of women after maternity (Borrueco et al., 2023).

Finally, overcoming the aforementioned adverse situations and possessing the freedom of choice to have control over one's life is associated with empowerment. Many women have ambitions to advance in their sporting careers (Drury et al., 2022; McGinnis et al., 2005), striving to break down gender barriers, being active agents of social change (Fernandez-Lasa, 2019; Norman and Simpson, 2022). The presence of women in leadership positions is paramount to achieve role models that guide future generations to thrive in their sporting careers (LaVoi, 2016). A woman in high leadership positions feels free to challenge any stereotypical behaviour or gender role assigned by traditional society (Claringbould and Knoppers, 2012). Another influential factor is the creation of mentoring programmes by women who have overcome discriminatory situations in sport, creating support groups that increase their self-confidence, self-esteem and security (Fernández-Lasa, 2019; Inglis, 2000; McGinnis et al., 2005). For this, an essential factor is the close support of sports organisations, giving them opportunities for growth and good rewards associated with the work done, which motivate them to continue promoting to high leadership positions (Molina-Hermosilla, 2016; O'Brien et al., 2023).

Theoretical foundation

The present study has been conducted on the basis of two gender theories, i) the theory of gender as a social structure (Risman, 2004) and ii) the theory of the sexual division of labour (Kanter, 1997a).

Gender theory as a social structure

The theory of gender as a social structure (Risman, 2004) explains a new classification of the mechanisms that contribute to gender outcomes within each dimension of social structure. This theory is based on the existence of a whole society that presents a gender structure that affects individuals and organises expectations linked to their social positions (Risman, 1998). This concept is constructed through traditional gender theories, such as the existence of biological (Udry, 2000), social (Bem, 1993) or sexist behavioural differences (Epsteins, 1988). All this has an impact on the creation of inequality through the expectations of others (West and Zimmerman, 1987).

This theory differentiates people's opportunities and limitations according to their sex, conceptualising gender as a social structure in order to analyse how gender integrates the following three dimensions: (i) Individual Level, based on the construction of the 'self', through socialisation, internalisation, identity work and the construction of gender; (ii) International Cultural Expectations, related to the cultural expectations developed by individuals, because men and women face different cultural expectations even though they occupy the same structural positions; and (iii) Institutional Domain, based on the construction of governmental gender practices, with explicit regulations regarding the distribution of resources and material goods.

Theory of the sexual division in the workplace

The theory of the sexual division of labour (Kanter, 1977a) shows a segregated organisational structure where there is limited progression to leadership positions for women in organisations. This organisational structure shapes and defines women's behaviour rather than women's intrinsic factors. The critical variables that explain the scarcity of women in senior positions relate to i) the position or position they hold within the organisation, ii) the power they wield in their positions, and iii) the proportional distribution of jobs.

Thus, according to the author, there are two types of situations: advantageous work situations and disadvantageous work situations. The former are associated with power and good opportunities for promotion, occupied by a majority social category, such as men; however, the latter are associated with limited opportunities, with the female sex being the priority in these positions. Thus, there is a position of dominance where women are relegated to the lowest positions, due to a system of prejudices that discriminate against women, making it impossible for them to develop towards leadership positions, thus creating the so-called glass ceiling.

Within this context, the concept of the 'token' woman (Kanter, 1997b) appears, associated with all women who carry out occupations socially assigned to the male gender and who are excluded because they are a minority group. These women have to face a series of conflicts, associated with these three essential aspects: i) visibility - the dominant group (men) observes in detail the behaviours of the minority group (women) generating an atmosphere of pressure; ii) polarisation - separation from the dominant group by feeling the minority and experiencing the existing differences; iii) assimilation - the attributes of the minority group disappear in order to be accepted and fit in with the attributes of the dominant group, imposing roles that limit their development.

METHOD

Sample

The sample to analyse the validity of the instrument and the calculation of reliability consisted of a total of 1,373 persons, divided into i) coordinator-researcher group (n = 4); ii) expert panel group (n = 8); iii) comprehension validity group (n = 20); pilot group 1 (n = 442) and pilot group (n = 899). Purposive sampling was carried out in the different groups of the study.

The main characteristics of the sample used for validation, concerning pilot group 2, are shown in Table 1. Firstly, the sample consisted of a total of 899 people, the mean age of the study participants was 36.05± 13.1 years; in relation to the sex of the population, 61% were male and 39% were female. The majority had completed higher education (31.1%) or postgraduate education (30.7%) and were employed full-time (54.8%). According to marital status, 51.7% of the population was single, while 43% were married; the majority of the sample had no children (61.9%).

Table 1. Sociodemographic variables of the study.

Variables	M (SD)
Age	36.05 (13.1)
	N (%)
Sex	
Male	549 (61.0)
Female	350 (39.0)
Education	
I finished primary school	12 (1.3)
I finished high school	77 (8.6)
I am in high school	30 (3.3)
I am in university	126 (14.0)
I finished university	280 (31.1)
I am doing a post-graduate degree	65 (7.2)
I finished a post-graduate degree (masters or other)	276 (30.7)
Other	29 (3.2)
Occupation	
Full-time employee	489 (54.8)
Employed part-time	172 (19.3)
Unemployed	54 (6.1)
Student	160 (17.8)
Retired	17 (1.9)

Marital Status	
Single	463 (51.7)
Married	385 (43.0)
Living with a partner	41 (4.6)
Separated	6 (0.07)
Divorced	0 (0.0)
Widowed	0 (0.0)
Children	
Yes	341 (38.1)
No	553 (61.9)
Function in Sport	
Athlete	389 (43.2)
Coach	220 (24.5)
Referee	0 (0.0)
Sport manager	131 (14.6)
Other	159 (17.7)
Sports Modality	
Individual sports	496 (55.2)
Collective sports	205 (22.8)
Mixed sports	198 (22.0)
Years involved in the sport	
Less than 5 years	48 (5.3)
5 to 10 years	143 (15.9)
10 to 15 years	185 (20.6)
15 to 20 years	161 (17.9)
More than 20 years	361 (40.2)
Sports Organization	
North America	329 (36.6)
Central America	133 (14.8)
South America	437 (48.6)
Global Rank	
Global North	329 (36.6)
Global South	570 (63.4)
Monetary remuneration	
I receive nothing	208 (23.6)
Less than $500	170 (19.3)
501 to $1,200	185 (21.0)
1,201 to $1,800	100 (11.4)
1,801 to $2,500	67 (7.6)
2,500 or more	151 (17.1)

On the other hand, it can be seen that the majority were athletes (39.8%), followed by coaches (34.4%), other functions - press, health, staff - (14.3%) and sports leaders (11.5%); most were associated with an individual sport (55.2%), with more than 20 years of experience (40.2%). In terms of the sports organisation represented, 48.6% were from South America, 36.6% from North America and 14.8% from Central America. In line with the global division indices (social, economic and political), the majority belonged to the Global South (63.4%). Finally, 23.6% received no monetary remuneration for their sporting duties and 21% received between $501 and $1,200.

Instrument

The final design of the questionnaire is composed of a total of 16 items divided into the following three dimensions: A) Sport Growth (SG), subdivided into Accessibility and Growth (SG-AG) and Work-Family

Balance (SG-WFB); B) Material Barriers (MB); and C) Empowerment (EM). The structure is set out in Table 2.

Table 2. Final version of the CIGED questionnaire.

Dimensions and items
DIMENSION 1. SPORT GROWTH (SG)
1A. Accessibility and Growth (SG-AG)
SG-AG1. I have faced difficulties starting my career in sports.
SG-AG2. I consider it difficult to move up in my career in sports.
SG-AG3. I have an elevated economic cost to travel to my sport related work.
1B. Family and work balance (SG-WFB)
SG-WFB1. I have to have another job to economically sustain my life in sport.
SG-WFB2. I have to find work and academic programs with flexible schedules to continue my work in sport.
SG-WFB3. I have thought/plan to leave my work in sport to focus on my familial, work, and academic life.
DIMENSIÓN 2. MATERIAL BARRIERS (MB)
MB1. I do my sport functions in good quality facilities.
MB2. I have favourable hours to do my work in sport.
MB3. I have easy access to the sports facilities to do my work at any hour.
DIMENSIÓN 3.EMPOWERMENT (EM)
EM1. I can overcome adverse situations alone that arise in my career in sport.
EM2. My work in sport makes me feel optimistic and satisfied.
EM3. Overcoming adverse situations in sport has helped me to have more confidence and self-esteem.
EM4. I believe my experience can be important to help other people advance their own careers in sport.
EM5. I think that my role in sport helps to reduce gender inequality.
EM6. Now I think that I have better control of my life than in the beginning of my sports career.
EM7. I have opportunities to accept a position of power and leadership within my career in sport.

Procedure

The design and validation of the Conditionalities of Effective Gender Equality in Sport (CIGED) questionnaire was carried out in several phases, following the procedure proposed by Carretero-Dios and Pérez (2005) on the design and validation of a new questionnaire. First, a review of the existing international literature on gender inequality in sport was carried out. Numerous studies were identified that proposed a qualitative approach and few studies that presented a quantitative approach using a closed-ended questionnaire. Thus, in order to address a second phase of initial questionnaire design, the numerous results of qualitative studies were categorised into five study dimensions. Thus, the initial proposal presented five dimensions and 69 items: Social Recognition (SR), Accessibility and Growth (AG), Material Barriers (MB), Work and Family Balance (WFB) and Empowerment (EM).

Then, in a third phase, a letter of collaboration as an expert judge was elaborated and sent to 22 people to assess the validity of the content. The fourth phase of the procedure consisted of quantitative interpretation, through the Aiken V assessment, and qualitative interpretation, through the comments and suggestions of the panel of experts. Subsequently, a comprehension validity analysis phase was carried out with 20 amateur female football players.

A first pilot study was then carried out: i) convenience sampling of 442 women, who played their role as sportswomen, coaches, referees or women in sports leadership positions in Spanish sport. However, the construct reliability was not favourable, so a second pilot study was carried out: ii) convenience sampling of 899 women and men who performed their sporting role at the Pan American Games in Santiago de Chile, held between 20 October and 5 November 2023.

The questionnaire was distributed telematically, via the online platform for the distribution of surveys of the University of Murcia and completed voluntarily and anonymously. Finally, the results extracted from these studies were used to address the final phase of analysis of validation and reliability of the questionnaire.

Data analysis

The data analyses of the psychometric properties of the scale were carried out using the SPSS v.26.0 statistical program of the University of Murcia. The construct validity for the Exploratory Factor Analysis (EFA) was carried out using the FACTOR v.12.01.02 program, with the Maximum Likelihood (MV) extraction method and the Oblimin Direct rotation method. Unweighted Least Squares (ULS) statistical analysis was performed for three factors. The programme used for the Confirmatory Factor Analysis (CFA) was Jamovi v.2.5.5. Other indicators were also taken into account such as the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy, the analysis of replicability with the GH Index, the Barlett's test of sphericity, the analysis of variance, and the measure of skewness and kurtosis. To analyse the reliability of the questionnaire, Cronbach's Alpha, Compact Reliability (CF) and Average Variance Extracted (AVE) tests were performed. Finally, Pearson's analysis was used to calculate the correlation between variables.

RESULTS

The main results of the scale design and validation study are shown below. Firstly, the action of the experts is shown, followed by the analysis of the psychometric properties of the scale, the Exploratory Factor Analysis, the Confirmatory Factor Analysis and finally, the specific analysis of the reliability.

Content validity analysis by panel of experts

The content validity analysis of the questionnaire was carried out with the opinion of a panel of experts on a total of 69 items divided into the five dimensions of the study. After the analysis of each item and dimension, the Aiken V analysis was carried out with the items that were not eliminated. The 34 items selected for a pilot proposal of the questionnaire obtained a mean Aiken's V score of 0.92 (95%CI: 0.83 - 0.96), without finding any value lower than 0.8 points.

The Likert-type scale was the most appropriate rating scale chosen by the expert judges and the coordinating group of the study, finally proposing a Likert scale with 7 anchors: 1 'strongly disagree' and 7 'strongly agree'.

Analysis of the psychometric properties of the scale

The analysis of the psychometric scale properties is detailed in Table 3. This analysis was developed according to the following aspects: i) Correlation of the item with the other items of the factor; ii) Mean (M); iii) Standard Deviation (SD); iv) Variance ($\sigma 2$); v) Cronbach's Alpha (α-C) if the item is eliminated; vi) Skewness (S); and vii) Kurtosis (K).

All items showed adequate results for the presented variables of the psychometric properties of the scale; furthermore, the total scale achieved favourable reliability data.

Exploratory factor analysis

The statistical analysis used to examine the construct validity was ULS, with a total sample of 899 people working in high-performance sport. Firstly, the sample adequacy reflected positive values, close to 1, with a KMO measure of 0.87 points and a Communality ratio of 0.99 points. Also, significant and favourable results were found in Bartlett's test of Sphericity, with X^2 7.524 (gl = 253; p > .001). Thus, it was possible to affirm that the data collected were adequate to carry out the PFA.

Table 3. Psychometric properties of the scale.

Item	Correlation	M	SD	σ2	α-C without the item	S	K
AG1	0.621	3.54	1.9	3.61	0.473	0.342	-0.968
AG2	0.583	3.45	1.9	3.56	0.523	0.391	-0.887
AG3	0.366	3.38	2.1	4.43	0.800	0.404	-1.19
WFB1	0.544	2.96	2.1	4.61	0.593	0.767	-0.779
WFB2	0.556	2.96	2.1	4.26	0.582	0.763	-0.691
WFB3	0.480	4.11	2.3	5.27	0.677	0.004	-1.51
MB1	0.688	5.35	1.8	3.09	0.724	-0.942	-0.067
MB2	0.645	5.46	1.7	2.76	0.769	-0.988	0.150
MB3	0.675	5.08	1.9	3.77	0.742	-0.765	-0.601
EM1	0.571	5.86	1.3	1.69	0.846	-1.26	1.68
EM2	0.701	6.04	1.2	1.35	0.829	-1.37	2.02
EM3	0.722	6.23	1.1	1.19	0.828	-1.69	3.33
EM4	0.706	6.29	1.1	1.10	0.831	-1.69	2.97
EM5	0.473	5.74	1.6	2.66	0.869	-1.36	1.18
EM6	0.680	5.89	1.4	1.83	0.830	-1.45	2.02
EM7	0.634	5.88	1.4	1.93	0.837	-1.32	1.23

Once the ULS factor analysis was carried out with the questionnaire of 34 items and five dimensions, it was established that the most appropriate analysis was for a total of three factors and 22 items. Within the first factor, items from the SG, WFB and MB dimensions were grouped, in the second factor, four items from MB were respected, and in the last factor, two items from RS were related to EM. Accordingly, a subdivision of the first factor was carried out, applying the ULS technique for the division of the first factor into two groups, which proved to be adequate.

On the other hand, the calculation of the GH-Index was 0.898 points for the first factor, followed by 0.838 for the second factor and 0.867 for the last factor. These results suggest a well-defined latent variable (>0.80), which allows ensuring a good replicability of the scale and dimensions in other possible investigations (Ferrando and Lorenzo-Selva, 2018). Finally, the observed variance of the total items of the questionnaire, assigned to each factor, reflected 13% of the variance for the first factor, 17.3% for the second and 11.5% for the third; thus, the total accumulated percentage of variance was 41.8%. Table 4 below shows the analysis of the ULS factor model with factor structure, factor loadings and communalities (com).

Table 4. Exploratory factor analysis with the ULS model.

Items	F1	F2	F3	F4	Com
Factor 1 – Sport Growth (SG)					
Factor 1.A. Sports Growth - Accessibility and Growth (SG-AG)					
1. I have to make more efforts to prove that I am able to perform my sport duties#	0.33				0.12
2. I have experienced situations in sports that have made me feel socially undervalued by other people#	0.42				0.18
3. I have an elevated economic cost to travel to my sport related work #	0.48				0.25
4. I have faced difficulties starting my career in sports#	0.69				0.50
5. I consider it difficult to move up in my career in sports#	0.69				0.49
Factor 1.B. Family and work balance (SG–WFB).					
6. I consider that having children interferes or may interfere with my sports career#	0.49				0.23
7. I have to find work and academic programs with flexible schedules to continue my work in sport#	0.57				0.34
8. I have thought/plan to leave my work in sport to focus on my familial, work, and academic life#	0.70				0.50
9. I have to have another job to economically sustain my life in sport#	0.54				0.33

Factor 2 - Material Barriers (MB)			
10. I have sufficient and adequate material to carry out my sport duties.	0.76		0.76
11. I do my sport functions in good quality facilities.	0.83		0.83
12. I have favourable hours to do my work in sport.	0.68		0.68
13. I have easy access to the sports facilities to do my work at any hour.	0.79		0.79
Factor 3 – Empowerment (EM)			
14. My family supports and respects my career and involvement in the sport.		0.34	0.17
15. My close environment has been supportive enough to start my sports career.		0.32	0.21
16. I can overcome adverse situations alone that arise in my career in sport.		0.63	0.42
17. My work in sport makes me feel optimistic and satisfied.		0.76	0.63
18. Overcoming adverse situations in sport has helped me to have more confidence and self-esteem.		0.82	0.66
19. I believe my experience can be important to help other people advance their own careers in sport.		0.81	0.63
20. I think that my role in sport helps to reduce gender inequality.		0.52	0.27
21. Now I think that I have better control of my life than in the beginning of my sports career.		0.71	0.52
22. I have opportunities to accept a position of power and leadership within my career in sport.		0.68	0.49

Note: #: Inverse items.

Confirmatory factor analysis

Once the FEA had been carried out, the CFA was performed, with the proposal of three dimensions and 22 items. Table 5 below shows the main results of the CFA, in relation to the estimated error (EE), the 95% confidence interval, the test statistics (Z; p) and the standardised estimator (Est).

Table 5. Confirmatory factor analysis of the scale.

Items	EE	**Confidence interval 95%**		Z	*p*	Est
		Inf.	Sup.			
Factor 1 – SG						
SG – AG						
SG-AG1#	0.06	1.43	1.67	25.8	.001	0.81
SG-AG2#	0.06	1.40	1.64	25.6	.001	0.81
SG-AG3#	0.07	0.78	1.07	12.5	.001	0.44
SG – WFB						
SG-WFB1#	0.09	1.42	1.76	18.4	.001	0.74
SG-WFB2#	0.08	1.15	1.44	17.2	.001	0.63
SG-WFB3#	0.10	1.53	1.91	17.8	.001	0.75
Factor 2 - MB						
MB1.	0.05	1.27	1.49	25.8	.001	0.79
MB2.	0.05	1.15	1.36	25.2	.001	0.78
MB3.	0.06	1.39	1.63	26.5	.001	0.81
Factor 3 - EM						
EM1.	0.04	0.75	0.90	20.8	.001	0.65
EM2.	0.03	0.84	0.97	26.7	.001	0.78
EM3.	0.03	0.83	0.96	28.8	.001	0.82
EM4.	0.03	0.75	0.87	26.2	.001	0.77
EM5.	0.05	0.70	1.91	15.0	.001	0.50
EM6.	0.04	0.89	1.05	23.6	.001	0.71
EM7.	0.04	0.85	1.02	21.7	.001	0.67

Note. #: Inverse items.

The final results detailed a valid final questionnaire for three dimensions and 16 items: Sports Growth - 6 items (1.A. Accessibility and Growth - 3 items; 1.B. Work-Family Conciliation - 3 items); Factor 2. Material Barriers - 3 items; and Factor 3. Empowerment - 7 items. In this way, a total of six items were eliminated in order to obtain favourable results in the WFB, especially in reliability and variance; three items belonging to SG, one item to MB and two items to EM. The two items eliminated in the third factor were the only ones that were related to the initial dimension of Social Recognition, which were grouped together in the AFE to the Empowerment dimension. This final model presented adequate test values for exact fit (Table 6) and for the fit measures (Table 7).

Table 6. Test for exact fit.

χ^2	gl	*p*
450	97	< .001

Note. χ² = Chi-square; Gl = degrees of freedom; p = significance.

Table 7. Adjustment measures.

				IC 90% del RMSEA	
CFI	**TLI**	**SRMR**	**RMSEA**	**Lower**	**Upper**
0.94	0.92	0.05	0.06	0.06	0.07

Note. CFI = Comparative Fit Index; TLI = Tucker-Lewis Index; SRMR = Root Mean Square Residual; RMSEA = Root Mean Square Error of Approximation; CI = Confidence Interval.

In relation to construct reliability, the measures of factor loadings (λ) and factor loadings squared (R2) of the items; and Cronbach's Alpha (α-C), McDonald's Omega (ω), composite reliability (CF) and average variance extracted (AVE) of the scale factors are shown below in Table 8.

Table 8. Reliability of the scale.

Items	λ	R^2	α-C	ω	FC	AVE
Factor 1			0.79	0.79	0.85	0.50
Factor 1A			0.70	0.74	0.74	0.50
1	0.81	0.66				
2	0.81	0.66				
3	0.44	0.19				
Factor 1B			0.71	0.71	0.75	0.50
4	0.74	0.55				
5	0.63	0.40				
6	0.75	0.56				
Factor 2			0.81	0.82	0.84	0.63
7	0.79	0.62				
8	0.78	0.61				
9	0.81	0.66				
Factor 3			0.86	0.8	0.87	0.50
10	0.65	0.42				
11	0.78	0.61				
12	0.82	0.67				
13	0.77	0.59				
14	0.50	0.25				
15	0.71	0.50				
16	0.67	0.45				

Finally, in relation to discriminant validity, the data resulting from Pearson's correlation between dimensions was compared with the square root of the AVE, being higher in all factors. In this way, it can be determined that the scale groups dimensions related to each other (convergent) and that, in turn, each one assesses a different subject (divergent). These data are presented in Table 9.

Table 9. Correlations between questionnaire factors and square root of AVE.

Factors	F1- CD	F2 - BM	F3 – EM
Factor 1 – SG	**0.71**		
Factor 2 – MB	0.23***	**0.79**	
Factor 3 – EM	-0.01	0.30***	**0.71**

*Note. *** Highly significant correlations for p < .001.*

DISCUSSION

The main objective of this study was to design and validate a questionnaire that assesses the determinants of effective gender equality in sport. In line with the literature review previously conducted and other reviews analysed (Janelle et al. 2020; Kavoura and Kokkonen, 2021; Laudares and Schwartz, 2020; Valentí et al., 2018), most studies on the subject addressed a qualitative methodology, with a reduced number of quantitative studies. Thus, new studies with a quantitative approach are essential to contribute to the in-depth analysis of current gender equality.

Within this quantitative methodology, the priority is to design and validate new tools to complement the scarce existing information. Currently, some questionnaires have been located that analyse the gender barriers perceived by women in the sports context. The most recent, designed and validated by Segado et al. (2022), analysed the obstacles and benefits perceived in Spanish female refereeing, through dimensions related to institutional support, the benefits of refereeing and the perception of a social and family climate. On the other hand, the BSCQW (Barriers to Sport Coaching Questionnaire for Women) tool by Kubayi et al. (2020), based on the socioecological model (LaVoi and Duvote, 2012), was also identified. This tool analysed the barriers perceived by female coaches, located in South Africa, in an intrapersonal, interpersonal, organizational and sociocultural context.

Both quantitative tools mentioned above are focused exclusively on a population group, female coaches or referees; while the tool presented in this study collects information on a varied sample, with items adapted to people who carry out different roles in: i) management positions, ii) sports training - coach, iii) refereeing and iv) sports life - athlete. In addition, it designs more specific dimensions oriented to co-responsibility and compatibility with sports and family life, specific material barriers encountered in the sports context, opportunities for sports growth and psychological aspects related to overcoming adverse situations in terms of gender inequality, through their empowerment.

On the other hand, it is important to mention that a first version made for the validation of the questionnaire, carried out only with a sample of women, was valid but not reliable. In contrast, the two questionnaires mentioned above, by Segado et al. (2022) and LaVoi and Duvote (2012), also used only a sample of women, but were valid and reliable. The difference found between these cases is the different objective of the study; while these two questionnaires proposed an exclusive analysis of the perception of barriers for women, the current study tool aims to assess the existence of effective gender equality between women and men. Accordingly, it is affirmed and justified that the second version carried out with a population of women and men, aligning the study in terms of gender perspective, presents valid and reliable results for a questionnaire that analyses the determinants of effective gender equality in sport. Gender mainstreaming, in global strategies, is the most practical means to achieve gender equality and women's empowerment (UN Women, 2020). Furthermore, this incorporation is also essential in the scientific literature, leading to real and effective changes in institutions, entities and research centres (Jiménez-Picón and Romero-Martín, 2020).

Regarding the main results of the validation of the study, firstly, a group of eight experts in the field, with a professional and/or academic profile, was formed. This group helped to design the structure of the questionnaire, with important quantitative and qualitative contributions on the content, in terms of quality, wording and final assessment. Subsequently, after conducting the Exploratory Factor Analysis for a sample of women and men, the five study variables and 34 items were changed to three dimensions and 22 items: i) Dimension 1 - Sports Growth - 9 items (1.A. Accessibility and Growth - 5 items; 1.B. Work-Family Balance - 4 items); ii) Dimension 2 - Material Barriers - 4 items; and Dimension 3 - Empowerment - 9 items. Within the first dimension, four items from the Accessibility and Growth group, one item from Material Barriers and four items from Work-Family Balance were grouped together, forming two sub-dimensions after reapplying the ULS technique, within Sporting Growth. Four items were maintained in Material Barriers, and two items of Social Recognition were added to the Empowerment dimension.

Subsequently, after performing the Confirmatory Factor Analysis and the Reliability analysis, the questionnaire presented a final structure of three dimensions and 16 items, eliminating a total of six items in order to present favourable validity and reliability values. The final structure of the questionnaire is composed of a first dimension called Sports Growth, which groups, on the one hand, contents related to Accessibility and Growth and, on the other hand, Balance with Work and Family. The SG-AG subdimension is composed of a total of three items related to the ease of access to sporting life at the beginning, the perception of being able to move up and progress within it, and how it can influence an economic and essential aspect, such as the cost of transportation. According to Valencia et al. (2011) the ease of transportation increases demand, if these costs are lower, there may be greater sport participation. The SG-WFB subdimension groups a total of three items, related to the obligation to have a job, and the flexible nature of the same, to be able to perform sports functions, and the possible abandonment of sporting life due to the inability to combine family, work or academic life. The support and improvement of these aspects, such as maternity or salary retribution, directly influences individual promotion, being essential factors in the growth of sporting life.

On the other hand, the Material Barriers dimension analyses the existence of good conditions in relation to infrastructures and flexible accessibility, and the schedules established for the realization of sporting life. In relation to the last dimension of the questionnaire, Empowerment, the two items associated with Social Recognition were eliminated, totally eliminating this dimension after the relationship of the CFA. The contents addressed in EM are linked to overcoming adverse situations during sporting life; increased satisfaction, optimism, confidence and self-esteem; the perceived ability to be able to help others in their sporting life; the important role assigned to reduce gender inequality in sport; increased control over one's own life; and the perceived opportunities to access a position of leadership and power.

Finally, the main theories of the study i) Gender theory as social structure (Risman, 2004) and ii) Division of labour theory (Kanter, 1977a) are related to the dimensions of the study. The theory of gender as a social structure (Risman, 2004) presents the existing hierarchy in a society created by the expectations of other people, based on sex and/or gender. The existence of gender stereotypes and prejudices, which invalidate the competencies of women in the development of their sports functions (Donoso et al., 2022; Mérida et al., 2022; Norman and Simpson, 2022) continue to exist today; as does an undervaluation of women with the use of sexist language (Yildizer et al. 2021). In this way, this theory is directly related to the first dimension of the Sport Growth questionnaire, especially with the Accessibility and Growth subdimension, where the ease of access and the perception of progression in sporting life are exposed, being able to influence the social structure in it. The second dimension Material Barriers is also closely related to this theory, as the distribution of resources and opportunities, on numerous occasions, are not equally distributed between genders, especially as a consequence of existing gender roles and social invalidation. Examples are for example the scarcity of financial resources, sponsorships, adequate facilities and schedules, and the warmth of material resources (Doğusan and Kiçak, 2021; Bowes et al., 2020; O'Brien et al., 2023).

In relation to the other theory linked to the study, on the division of the work environment (Kanter, 1977a), the experiences of women in the work environment and the limited progression to high leadership positions in organizations are mainly exposed. Thus, the Work-Family Balance subdimension, within the Sports Growth dimension, is directly related, for example, to the lack of maternity support and family life reconciliation programs (Borrueco et al., 2023; Culvin and Bowes, 2021). Progression to leadership positions directly influences the Empowerment dimension, where some perceived limitations are related to horizontal segregation - limited opportunities for promotion and vertical segregation - grouping of roles and tasks according to gender; existence of stereotypes such as low social belief in their abilities as leaders; and, among others, lack of support from sports organizations (Bowes and Kitching, 2021; Donoso et al., 2023; Klavanes et al., 2020; Organista, 2020). Finally, it is important to overcome these adverse situations and have ambition to promote in their sport careers (Drury et al., 2022); feeling free to challenge any sexist behaviour and participating as an agent of social change that helps to achieve gender equality in society (Fernandez-Lasa, 2019; Norman and Simpson, 2022).

CONCLUSIONS

The main conclusions of the study state that a validation carried out exclusively with women does not show adequate reliability values; however, it can be confirmed that the questionnaire is valid and reliable for a sample of women and men, respecting the principle of gender perspective. First of all, the group of experts participates positively in the design of the questionnaire content, presenting an initial proposal of five dimensions and 69 items, which are reduced to 34 items divided into the five dimensions established. A quantitative analysis is carried out with comments and suggestions from the experts, and a quantitative analysis showing favourable values for the Aiken V.

In relation to the statistical analysis of the CIGED scale, we performed the AFE, stating, firstly, that the data collected from the sample were adequate for the analysis. The Unweighted Least Squares (ULS) factor analysis technique was used, reducing the questionnaire to three factors and 22 items. Subsequently, the CFA and reliability analysis is carried out, eliminating a total of six items to confirm the validity and reliability of the scale. Favourable data are obtained in the test for exact fit and in the fit measures, with favourable CFI, TLI, SRMR and RMSEA indicators. In addition, the scale manifests favourable reliability data in Cronbach's alpha, composite reliability and mean variance extracted.

In line with the discriminant validity, it is determined that the scale groups dimensions related to each other (convergent) and that, in turn, each one evaluates a different subject (divergent). Also, the psychometric properties of the scale showed adequate values for variance, correlation, skewness and kurtosis.

After the analysis of the evaluation of the group of experts, the AFE, the AFC and the reliability analysis, the CIGED scale was found to be a valid and reliable questionnaire for a sample of women and men. The final structure of the questionnaire is as follows: Dimension 1. Sports Growth - 6 items (1.A. Accessibility and Growth - 3 items; 1.B. Work-Family Balance - 3 items); Dimension 2. Material Barriers - 3 items; and Dimension 3.

Finally, the main practical implications are related to the implementation of the questionnaire in different sports contexts, with the aim of analysing the existing effective equality. This questionnaire can be used in various population groups, both for women and men, who develop their sporting life as athletes, coaches, referees and people in leadership positions. In this way, it contributes to the increase of studies on gender perspective, in order to analyse the existing situation and to develop positive action measures that approach the achievement of effective equality in sport. Finally, the principle of intersectionality can be taken into account in these future studies, selecting the study variables related to a possible situation of multiple discrimination in sport.

Limitations

The main limitations are associated with the sample size. A first validation of the study was carried out only with European women, where the data were not reliable and the information collected from this sample could not be used. In the second validation, a similar sample is not obtained between men and women, with a larger male population; also, the sample does not manage to represent the entire event.

In relation to the characteristics of the instrument, after the validation, the Social Recognition dimension was completely eliminated, and there were no items distributed in other dimensions. Also, the correlation analysis does not show strong relationships between the dimensions of the questionnaire.

AUTHOR CONTRIBUTIONS

All authors have contributed to all phases of the project. María Carboneros: design of the study, development of the theoretical bases, analysis and interpretation of the data and writing of the article. José María López-Gullón: study design, data collection, writing the article. Salvador Angosto: study design, data collection, data analysis and interpretation, and writing of the article.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Comparison of psychological factors between healthy athletes and those suffering from chronic ankle instability

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ABSTRACT

Background: Ankle sprain is the most common traumatic injury among handball players, which usually leads to the development of Chronic Ankle Instability (CAI). There is much evidence regarding the mechanical component about this condition; however, the psychological component has been little studied in previous research. The aim of this study was to compare anxiety, personality traits, depression, and kinesiophobia between young handball players with and without CAI. Methods: Case-control study. A sample of 100 young handball players was recruited and divided into athletes with CAI (case group, n = 50) and healthy athletes (control group, n = 50). Main outcome measures were anxiety, personality traits, depression and kinesiophobia levels, which were assessed by self-reported questionnaires (State-Trait Anxiety Inventory, Eysenck Personality Questionnaire, Beck Depression Inventory-II and Tampa Scale for Kinesiophobia-11). Results: Statistically significant differences were found between groups for anxiety, personality traits, depression and kinesiophobia. Case group showed higher levels of state anxiety (Δ-2.50; $p < .05$), trait-anxiety (Δ-3.80; $p < .05$), neuroticism (Δ-0.92; $p < .05$), depression (Δ-4.10; $p < .05$), and kinesiophobia (Δ6.82; $p < .05$) compared to the control group. Conclusions: Young handball players with CAI present significant greater levels of anxiety, neuroticism, depression and kinesiophobia compared to healthy young handball players.
Keywords: Handball, Adolescent, Biopsychosocial, Anxiety, Depression, Kinesiophobia.

Cite this article as:
San Antolín Gil, M., Ceballos Laita, L., Jiménez Del Barrio, S., Calvo Lobo, C., Rodríguez Sanz, D., Llamas Ramos, R., Llamas Ramos, I., & García García, D. (2025). Comparison of psychological factors between healthy athletes and those suffering from chronic ankle instability. *Journal of Human Sport and Exercise, 20*(2), 533-546. https://doi.org/10.55860/5crnev67

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Submitted for publication November 10, 2024.
Accepted for publication December 20, 2024.
Published February 10, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/5crnev67

INTRODUCTION

Handball is one of the most popular sports in the world in all age groups. The game is characterized by physical contact, sudden acceleration, jumps with hard landings, and twisting actions, which are related with a high risk of injury (Aman et al., 2016; Engebretsen et al., 2013; Junge et al., 2009). Young handball players aged between 15 to 19 years have shown the highest injury prevalence (41%) among all the age groups (Aman et al., 2016). The lower limbs registered the highest injury rates, and the ankle sprain is the most common traumatic pathology with a prevalence between 24.9 to 40% (Y de J, Nielsen AB, 1990) of the total injuries in young handball players generating a high sporting and economic burden (Asai et al., 2020; Bere et al., 2015; Giroto et al., 2017; Goes et al., 2020; Moller et al., 2012; Rafnsson et al., 2019).

Lateral ankle sprain is defined as an acute traumatic injury of the lateral ligament complex after an excessive inversion of the rear foot or a combined plantar flexion and adduction of the foot (Gribble et al., 2013). Around 40% of the young athletes with lateral ankle sprain developed CAI. CAI is characterized by multiple mechanical and sensorimotor dysfunctions such as plantar flexor, inversion, and eversion muscles weakness (Feger et al., 2016; Fraser et al., 2020; Gribble PA, Robinson RH, 2009; Ryman Augustsson S, Sjöstedt E, 2023), restricted ankle joint dorsiflexion (Fraser et al., 2020; Jamsandekar et al., 2022; Li et al., 2017), joint position sense (Alghadir et al., 2020; Nakasa et al., 2008; Witchalls et al., 2012) and force sense impairments (Simon et al., 2014; Sousa et al., 2017; Yen et al., 2019), static (Ryman Augustsson S, Sjöstedt E, 2023; Mitchell et al., 2008) and dynamic (Alghadir et al., 2020; Hoch et al., 2012) balance alterations, and kinetic and kinematic changes (Drewes et al., 2009; Koldenhoven et al., 2016; Ty Hopkins et al., 2012; Wright et al., 2016).

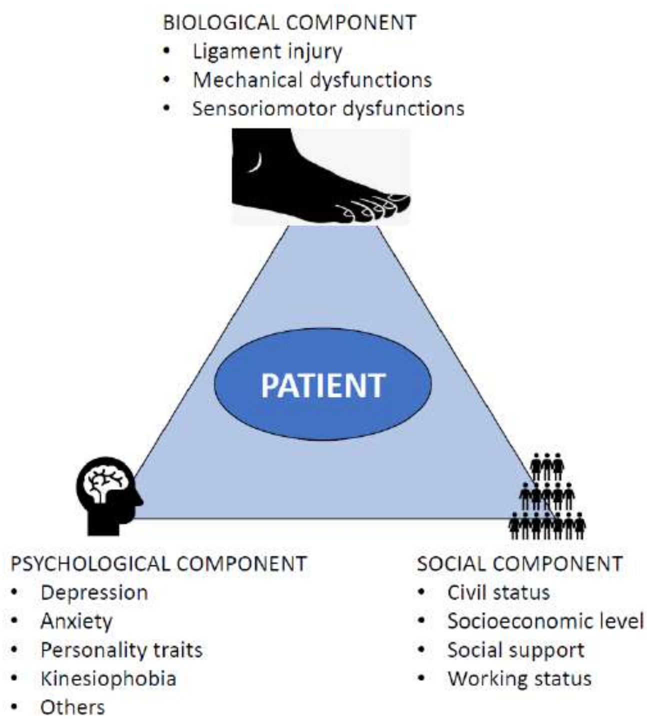

Figure 1. Biopsychosocial approach.

Despite of mechanical dysfunctions in patients with CAI are widely investigated, a high proportion of young athletes do not fully recover after an ankle sprain and have residual and chronic symptoms such as pain, swelling, ankle joint giving-way or recurrent injury (Ryman Augustsson S, Sjöstedt E, 2023; Baldwin et al., 2017; Hiller et al., 2012). Hertel et al. (2019) proposed a biopsychosocial model for patients with CAI in which not only biological factors but also personal, and environmental factors are involved (Figure 1). There is a lack of evidence on the role that the psychological component may play in the development and evolution of CAI, and research into this seems necessary. Conventional physical therapy modalities usually only address the biological component of CAI. It is likely that if the psychological and social components of the patient are not addressed as well, the therapeutic success will not be complete; this is what can lead to the chronification of the injury. In this sense, several authors have found differences between adults with musculoskeletal injuries and healthy matched controls in some psychological variables such as anxiety, personality traits, depression, and kinesiophobia (Kilic et al., 2017; San-Antolín et al., 2020).

Anxiety is defined as a mental disorder associated with psychological discomfort and which presents symptoms such as irritability, fear, avoidance, muscle pain, lack of memory, concentration difficulties and fatigue. Li et al. (2017) showed that athletes presented a higher incidence of anxiety having a two-fold increase in risk of suffering different types of injuries. Depression is one of the most common mental disorders in professional handball players with a prevalence of 26% and is characterized by the presence of symptoms such as y sadness, fatigue, sleep difficulties, feelings of tiredness and worthlessness, loss of interest and pleasure or appetite changes (Kilic et al., 2017). The same authors found that depression can have a negative impact on sport performance and injury recovery and that a higher number of severe sport injuries was related to the presence of symptoms of depression. Some personality traits, like adventurous spirit and lack of caution, have shown to be related with the risk of sport injuries (Junge A, 2000). In this regard, San Antolín et al. (2020) found that athletes suffering from myofascial pain syndrome exhibited higher neuroticism level compared with healthy athletes. Some authors have described that neuroticism is associated with higher levels of anxiety and injury risk and with states of hypervigilance to pain, which may be related to the development of chronic pathologies (San Antolín et al., 2020; Xu et al., 2024). Kinesiophobia is defined as an irrational fear of movement or physical activity that results in physical limitation and is due to feelings of vulnerability to pain or re-injury. Several authors concluded that athletes with higher levels of kinesiophobia showed a poorer physical condition because of the avoidance of activities (Fraser et al., 2020; San-Antolín et al., 2020; Houston et al., 2014).

Despite of the knowledge about the key role of psychological factors in adults with musculoskeletal injuries, there is a lack of evidence about the psychological profile of young handball players with CAI, which is the population group that has the highest incidence and prevalence rate of ankle sprains and CAI. Thus, the aim of this study was to compare the anxiety, personality traits, depression, and kinesiophobia between young handball players with and without CAI.

MATERIAL AND METHODS

Design

A case-control study was conducted between January 2022 and March 2023. The study was designed following the *Strengthening the Reporting of Observational Studies in Epidemiology* (STROBE) Statement Guide (Von Elm et al., 2008). Before patients´ enrolment, the Ethical Committee of the Hospital Clínico San Carlos (20/478-E) and the Ethical Committee of the European University of Madrid (CIPI/20/139) approved the study. The study was carried out following the Declaration of Helsinki (2013) and all the participants read the informant consent, agreed to participate, and signed the informed consent by themselves or by their parents or guardians depending on the age of the participant.

Sample size calculation

The sample size calculation analysis was performed for the difference between two independent means (two groups including case and control participants) using G*Power version 3.1.9.2 (G*Power©, University of Dusseldorf, Germany), considering a large effect size (Cohen d = 0.80) (Cohen et al., 1988) for a two-tailed hypothesis, a between group proportion of N/n = 1, and a power (1-β error probability) of 0.80 with an α level of .05, the minimum sample size required was 52 participants to achieve an actual power of 0.807.

Participants

Patients´ recruitment was carried out between January 2022 and March 2023 in the Hospital IMSKE (Valencia, Spain) following a sex-matched consecutive sampling method. A hundred young handball players participated in the study (50 athletes with CAI and 50 age-matched athletes without CAI).

Inclusion criteria

The sample consisted of handball players aged between 13 to 17 years, who practiced handball at least six hours per week. Participants were divided into two groups: the case group, which included young handball players with CAI, and the control group that included age-matched athletes without CAI.

- Case group: Young handball players were included in the case group if they met the inclusion criteria stated by the International Ankle Consortium (Gribble et al., 2013): 1) history of at least one significant LAS in the previous 12 months or more prior to the study and resulted in inflammation and impaired physical activity; 2) the most recent LAS must have occurred more than three months prior to the study enrolment; 3) two or more episodes of ankle giving-way, or recurrent LAS or feelings of instability at the injured ankle in the previous six months; 4) a score of 24 or less in the Cumberland Ankle Instability Tool (CAIT).
- Control group: Young handball players were included in the control group if they: 1) had no history of LAS or ankle instability; 2) were considered as coper (individual who is more than 12 months removed from the index ankle sprain, reports no or very minimal symptoms or deficit in self-reported function and perceives fully recovery) (Hertel J, Corbett RO, 2019); 3) had a score higher than 24 in the CAIT.

Exclusion criteria

The exclusion criteria were: 1) young handball players with history of previous surgeries in the foot, ankle or other regions of the lower limb; 2) any acute injury of other musculoskeletal structures of the lower extremity (such as sprains, strains and/or fractures) in the previous three months; 3) or young handball players with visual, vestibular or neurological impairments that could influence their balance. Although it was not considered an exclusion criteria, none of the participants were undergoing psychological treatment at the time of the study.

Socio-demographic and descriptive data

Descriptive data comprised sex (male or female), age, body mass index (BMI), playing position (goalkeeper, wing, back or line), use of foot insoles, use of ankle bandage or ankle brace and CAIT score.

Outcome measures

Psychological variables consisted of anxiety, personality traits, depression, and kinesiophobia and were measured using the Spanish adaptations of self-reported questionnaires. The questionnaires used in this study are chosen because they have adequate psychometric properties, are validated in Spanish, have been widely used in the literature and are easy for patients to complete.

Anxiety
Anxiety was measured using the Spanish State-Trait Anxiety Inventory (STAI). This questionnaire presented excellent internal consistency (Cronbach α: 0.90-0.93) and good test-retest reliability (ICC: 0.73-0.86) (Guillén-Riquelme, Buela-Casal, 2011). STAI measure two dimensions of anxiety: trait-anxiety, which determine the permanent anxiety level; and state-anxiety, which measure how the person feels at the moment. Each dimension has 20 items on a Likert-type scale of 0 (not at all) to 3 (very much), with higher scores indicating greater presence of anxiogenic symptoms.

Personality traits
Personality traits were measured using the Spanish abbreviated Eysenck Personality Questionnaire (EPQ-RA). This scale was used to determine four personality traits: neuroticism (level of emotional instability), psychoticism (level of hardness), extraversion (level of sociability) and sincerity (level of compliance) scores. This questionnaire has 24 items that evaluate these four dimensions using six items per scale and two YES/NO response alternatives. The greater the number of affirmative answers, the greater presence of each dimension in the subject's personality. This questionnaire presented an internal consistency ranging from 0.363 to 0.552 and a moderate-good reliability (ICC = 0.53-0.83) (Sandín et al., 2020).

Depression
Depression was assessed using the Spanish version of the Beck Depression Inventory-II (BDI-II) (Sanz et al., 2003), which had very good internal consistency (Cronbach α: 0.87) and retest reliability ranged from 0.73 to 0.96. BDI-II presents 21 Linkert-type items that measure different symptoms of depression, such as sadness, pessimism, feelings of failure, loss of pleasure, feelings of guilt, feelings of punishment, among others. Each item has a four-point scale (0,1,2,3), except items 16 and 18, which each have seven categories. The total score is categorized into minimal, mild, moderate, or severe depression, with a higher score linked to greater severity.

Kinesiophobia
Kinesiophobia was measured using the Spanish validated translation of the Tampa Scale for Kinesiophobia (TSK-11) (Gómez-Pérez et al., 2011). Acceptable psychometric properties have been shown with good internal consistency (Cronbach α: 0.79), and excellent test-retest reliability (ICC: 0.81) (Woby et al., 2005).). TSK-11 consists of 11 Lykert-type items from 1 (strongly disagree) to 4 (strongly agree). TSK-11 is divided into two subscales: activity avoidance and harm. Higher scores mean greater fear of pain and avoidance of movement.

Statistical analysis
Statistical Package for the Social Sciences (SPSS) version 25.0 for Windows was used for statistical analysis. Qualitative variables were presented as frequencies and percentages while quantitative variables were presented as minimum, maximum, mean and standard deviation. Before between-group comparisons, the normality and variances homogeneity were evaluated using the Kolmogorov-Smirnov and Levene test, respectively. Differences between young handball players with and without CAI were analysed using the Students´ t-test or the Mann-Whitney U test following the normal or non-normal distribution of the variables respectively. A p-value < .05 was considered statistically significant. To determine the effect size, the value of η^2 is obtained.

RESULTS

Socio-demographic and descriptive data

One hundred and seven participants were initially recruited for the study. After the elegibility criteria screening, seven participants were excluded. Four presented lower limb surgeries and three had acute musculoskeletal injury in the ankle or foot regions in the previous three months. Finally, one hundred young handball players met all the elegibility criteria (CAI group, n = 50; control group, n = 50).

No statistically significant differences were found for any demographic or clinical variables except for the use of bandages and the CAIT total score. In the CAI group, 34% (n = 12) of the young handball players reported using ankle bandages for training and/or matches, and the total CAIT score was 19.82 ± 4.26; while the control group used no bandages, and the total CAIT score was 28.64 ± 1.54 ($p < .05$). The detailed description of the demographic and clinical variables are shown in the Table 1.

Table 1. Demographic and clinical variables at baseline.

Demographic and clinical variables	Control group	CAI group	Statistical test	Significance (*p*-value)
Sex				
-Men	25 (50)	25 (50)		
-Women	25 (50)	25 (50)		1
Age (years)	14.02 (1.91)	14.16 (1.77)	$t(98) = -0.93$	.7
BMI[1] (Kg/cm^2)	21.24 (3.93)	21,76 (2.84)	$t(98) = -0.76$	.45
Position			X^2 (3) = 1.72	.63
-Goalkeeper	3 (6)	6 (12)		
-Wing	16 (32)	12 (24)		
-Pivoter	10 (20)	9 (18)		
-Backcourt	21 (42)	23 (46)		
Use of foot insoles			X^2 (2) = 0.45	.8
-Never	42 (84)	40 (80)		
-Only for sport	4 (8)	4 (8)		
-Sport and daily live	4 (8)	6 (12)		
Bandage			X^2 (2) = 13.64	**<.01**
-Never	50 (100)	38 (76)		
-For matches	0 (0)	8 (16)		
-Training and matches	0 (0)	4 (8)		
CAIT[2]	28.64 (1.54)	19.82 (4.26)	t(98) = 13.79	**<.01**

Note. [1]BMI: Body Mass Index; [2]CAIT: Cumberland Ankle Instability Tool.

Outcomes

Table 2 shows the between-groups comparison for all the outcome variables. Statistically significant differences were found between the CAI and control group for anxiety, personality traits, depression and kinesiophobia. Young athletes with CAI showed higher levels of state-anxiety (∆ 2.50; $p < .01$), trait-anxiety (∆ 3.80; $p < .01$), neuroticism (∆ 0.92; $p < .01$), depression (∆ 4.10; $p < .01$) and kinesiophobia (∆ 6.82; $p < .01$), compared to the control group. Considering the η^2 values, the effect size is medium for the variables state-anxiety, neuroticism, depression and harm (kinesiophobia). The effect size is large ($\eta^2 > 0.14$) for the variables trait-anxiety, avoidance activity (kinesiophobia) and total kinesiophobia. On the contrary, the effect size is small ($\eta^2 < 0.06$) for the variables psychoticism, extraversion and sincerity.

Table 2. Psychological outcomes (between-groups differences).

Outcome variable	Control group Mean (SD)	CAI group Mean (SD)	Between-group differences	Significance (*p*-value)	Effect size (η^2)
State-anxiety (STAI)	26.80 (4.14)	29.30 (4.69)	2.50	**<.01**	0.08
Trait-anxiety (STAI)	25.84 (4.91)	29.64 (4.77)	3.80	**<.01**	0.14
Neuroticism (EPQ-RA)	2.06 (1.71)	2.98 (1.70)	0.92	**<.01**	0.07
Psychoticism (EPQ-RA)	1.72 (1.28)	1.90 (1.22)	0.18	.47	0.01
Extraversion (EPQ-RA)	4.52 (1.45)	4.20 (1.53)	-0.32	.28	0.01
Sincerity (EPQ-RA)	3.32 (1.53)	3.80 (1.57)	0.48	.13	0.02
Depression (BDI-II)	8.76 (6.98)	12.86 (7.59)	4.10	**<.01**	0.08
Avoidance activity (TSK-11)	10.34 (4.09)	14.98 (3.12)	4.64	**<.01**	0.3
Harm (TSK-11)	9.22 (3.60)	11.40 (3.09)	2.18	**<.01**	0.1
Total kinesiophobia (TSK-11)	19.56 (7.21)	26.38 (5.53)	6.82	**<.01**	0.23

Note. SD: standard deviation; CAI: chronic ankle instability; STAI: state-trait anxiety inventory; EPQ-RA: Eysenck personality questionnaire revised abbreviated; BDI: Beck depression inventory; TSK: Tampa scale for kinesiophobia.

DISCUSSION

The aim of this cross-sectional study was to compare the psychological status between young handball athletes with and without CAI. Athletes with CAI showed statistically significant higher levels of anxiety, personality traits such as neuroticism, depression, and kinesiophobia than the age-matched controls.

Due to the results achieved in this study, psychological status may be an important factor in young handball players with CAI. To the best of our knowledge, there is a lack of evidence assessing the anxiety, personality traits and depression in young athletes with CAI. However, due to the design of the study it is not possible to determine the cause-effect relationship between CAI and psychological disorders; i.e., the results of the present study do not allow to conclude whether athletes with CAI present these psychological disorders as a consequence of the injury; or whether, on the contrary, athletes with certain psychological characteristics could be predisposed to the development of CAI after an initial ankle sprain. It might be interesting to carry out longitudinal studies in order to determine this causal relationship between CAI and the psychological disorders described in the present study.

Previous studies considered certain aspects of psychological status but did not include young athletes or did not carry out a specific evaluation. Kosik et al. (2020) concluded that in sample size of 59 adult athletes, the participants included in the CAI group presented higher levels of depression but not anxiety compared to a Copers group and a control group. Johnson et al. (2011) and Ivarsson et al. (2010) reported a higher anxiety level in injured athletes than in healthy ones. San Antolín et al. (2020), concluded that athletes with myofascial pain syndrome presented statistically significant higher levels of anxiety, neuroticism, and depression compared to healthy athletes. Cohen et al. (2018) found significant differences in neuroticism between professional and amateur athletes. Galambos et al. (2005) found higher levels of depression in injured athletes compared to healthy or asymptomatic athletes in a cohort of 845 young athletes. These studies showed similar results to the data reported in our study. However, all the studies included adult athletes, Kosik et al. (2020) used the Patient Reported Outcomes Measurement Information System to assessed physical, social and mental functioning, which cannot be considered a specific instrument to evaluate psychological status. Johnson et al. (2011), Ivarson et al. (2010) and San Antolín et al. (2020), did not consider the presence of CAI among the athletes. Galambos et al. (2005) used the Brunel Mood Scale to assess depressive symptoms, considering depression as a mood instead of a clinical entity by itself.

In general, anxiety, personality traits and depression have shown to be important factors practicing sports because may influence sport performance, injury risk and injury recovery. Some authors pointed out that athletes with higher levels of anxiety presented a two-fold risk of injury (Lobo et al., 2016), the presence of some personality traits were considered injury predictive factors (Ivarsson 2010) and can influence in the risk of injuries and in the outcome of the rehabilitation (Cohen et al., 2018), negative association between neuroticism and athleticism has also been showed in adolescents (Klein et al., 2016) and lower levels of positive reframing were related to higher levels of depression and an increased risk of traumatic injuries (Tranaeus et al., 2021; Yang et al., 2014). Thus, the psychological status understanding of the athletes may optimize the rehabilitation process and promote a faster and safer return to play (Truong et al., 2020). In this sense, Ramaligan et al. (2023) suggested that the inclusion of a psychological intervention to decrease anxiety improved pain intensity and ankle instability perception in adult athletes with CAI. On the other hand, no between-group differences were found on the variables psychoticism, sincerity and extroversion. Therefore, these personality traits did not seem to be related to injury risk in athletes. This is in line with findings found by other authors (San Antolín et al., 2020; Xu et al., 2024).

Kineshiophobia is the most investigated symptom in recreative and professional athletes with musculoskeletal injuries, including CAI. Our study found that young handball athletes with CAI presented higher levels of kinesiophobia, in the activity avoidance and in the harm subscales, compared to the control group. Several studies (Fraser et al., 2020; Houston et al., 2014; DeJong et al., 2019; Hadadi et al., 2020; Koldenhoven et al., 2019; Suttmiller et al., 2022; Terada et al., 2017) concluded that athletes with CAI presented higher levels of kinesiophobia compared to Copers or to healthy-matched controls using the short or the long version of the TKS questionnaire. In this sense, the presence of kinesiophobia in athletes leads to fear of movement and avoidance of activity behaviours. In addition, a negative association between kinesiophobia and foot and ankle function has been reported (Suttmiller et al., 2022). All of this may negatively affect the athletic performance. Kinesiophobia is a characteristic symptom also in other sport injuries such as anterior cruciate ligament rupture or Achilles tendon injury (Kvist et al., 2022). Clinical evolution of patients with these pathologies can also be improved by including a psychological approach.

All these findings described in the present study are in agreement with the results of the review by Tranaeus et al. (Tranaeus et al., 2024) in which the psychosocial component is reported to be a risk factor for overuse injuries and it is concluded that intervention programs based on acceptance practices, cognitive behavioural approach and social support can reduce negative reactions.

Clinical Recommendations: From a clinical perspective, considering the higher levels of anxiety, neuroticism, depression and kinesiophobia found in young handball players with CAI, it may be necessary to change the treatment approach for this pathology. The mechanical and local model should be changed for the biopsychosocial model proposed by Hertel and Corbett (2019). Patients suffering from CAI should be treated with multimodal psychological interventions such as mental imagery, coping strategies and cognitive restructuring educational techniques (Banatao et al., 2024), as well as deep breathing exercises (Ramalingan et al., 2023) to improve psychological deficits presented in these patients. Therefore, it seems interesting for sports clubs to include a psychologist within the medical staff; in this way, it will be possible to make a comprehensive approach to injured athletes, allowing their full recovery and their return to play. Future interventional studies should combine some physical therapy modalities and psychological interventions for the treatment of athletes with CAI.

Limitations: This study presents several limitations. First, only young handball players were included, so the results cannot be extrapolated to other groups. Second, the cross-sectional design does not allow associating the cause-effect of the differences achieved. Third, a random selection may be more appropriate than a consecutive sampling method for the recruitment process. Fourth, the inclusion of a Copers group was not considered. Fifth, confounding variables such as civil status, socioeconomic level, social support, working status or previous psychological diagnostics were no collected. Finally, despite our statistical analysis was performed using the Students´ t-test or the Mann Whitney U test following the normal or non-normal distribution, according to the calculated sample size based on the difference between two independent means (case and control groups), future investigations should perform longitudinal studies such as cohorts to apply analysis of variance and Bonferroni corrections to determine the differences among different measurement moments. Moreover, future studies should assess the psychological status in different age groups with CAI from different sports. In addition, gender differences should be considered in future analysis.

CONCLUSIONS

Young handball players with CAI present significant greater levels of anxiety, neuroticism, depression and kinesiophobia compared to healthy athletes. Therefore, it seems necessary to include psychological approaches in the treatment of athletes with CAI.

AUTHOR CONTRIBUTIONS

Daniel García García, César Calvo Lobo and David Rodríguez Sanz participated in data collection and execution of the field study. Marta San Antolín Gil, Rocío Llamas Ramos and Inés Llamas Ramos designed the study´s protocol and carried out the data processing. Luis Ceballos Laita and Sandra Jiménez del Barrio drafted the manuscript that subsequently was commented, revised and approved by all authors.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ACKNOWLEDGMENTS

We would like to thank Club Balonmano Nava and all the adolescents, parents and coaches who have been involved in this investigation.

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REVIEW ARTICLE

Recent trends in physical activity correlates among children and adolescents in China: A systematic review

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ABSTRACT

China, one of the most densely populated emerging nations, is confronted with an escalating problem of inadequate physical activity among its children and teenagers. This review systematically examines literature from the past five years to identify the latest trends in factors related to physical activity among Chinese kids and teenagers, aiming to provide information for formulating policies and intervention strategies tailored to China's national context. We searched six electronic databases (PubMed, Web of Science, Scopus, Cochrane Library, SPORTDiscus, and ERIC) for studies published between January 2019 and January 2024. A total of 30 articles met the inclusion criteria, with four employing longitudinal designs and three using objective tools to assess physical activity. Sample sizes ranged from 255 to 93,600 participants, with 23 studies involving more than 1,000 participants. The findings indicate that, compared to other countries, young people's physical activity in China is more strongly associated with parental support, physical exercise, family structure, and neighbourhood safety. Furthermore, research examining the correlation between school surroundings and physical activity is scarce. Future interventions should prioritize family-related factors and strengthen the collaboration between families and schools.

Keywords: Exercise, Factors, Correlation, Young people, Physical activity.

Cite this article as:
Meng, L., Abu Saad, H., Geok, S. K., Chuang, Y., & Guangtao, R. (2025). Recent trends in physical activity correlates among children and adolescents in China: A systematic review. *Journal of Human Sport and Exercise, 20*(2), 547-561. https://doi.org/10.55860/vxgmd576

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Submitted for publication November 22, 2024.
Accepted for publication January 08, 2025.
Published February 10, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/vxgmd576

INTRODUCTION

The numerous and well-documented health benefits of consistent physical activity for kids and teenagers are substantial. Participating in consistent physical activity during childhood and adolescence is crucial for sustaining a desirable body weight (Soares et al., 2023), promoting a healthy metabolism (Aadland et al., 2020), enhancing muscle function (Foster et al., 2020; Smith et al., 2014), and preventing chronic illnesses like diabetes and cardiovascular disease (Bila et al., 2023). Furthermore, research has demonstrated that engaging in moderate physical activity has a beneficial impact on the psychological well-being of young individuals (Biddle et al., 2019). Additionally, physical activity is being recognized as a possible approach to addressing and alleviating symptoms of depression (Jiang et al., 2023). These findings emphasize the multifaceted benefits of physical activity participation for young people, encompassing physical and psychological well-being.

Although the advantages of physical activity are well-known, new survey data reveals that the proportion of children and adolescents aged 6–17 in China who do not engage in physical activity has risen from 70.0% in 2004 to 81.5% in 2015, and this upward trend continues (Yang et al., 2020). Simultaneously, the time spent in sedentary mode has significantly increased from 23.9 ± 0.6 hours per week in 2004 to 25.7 ± 0.6 hours per week in 2015, with screen entertainment time showing a particularly notable increase of 2.9 hours per week. In general, the amount of physical activity among Chinese children and adolescents is plainly inadequate and demonstrates a continuous decline, while sedentary behaviour is consistently increasing.

The COVID-19 pandemic has significantly influenced people's lifestyles and habits. In China, this impact may have been intensified by an extended period of stricter public health measures imposed by the government to contain the virus's transmission. Hence, it is imperative to reassess the determinants linked to physical activity in Chinese children and adolescents. This endeavour would aid in pinpointing crucial components and provide valuable insights to steer the formulation of focused interventions in the times ahead. Furthermore, based on our current understanding, this research represents the initial investigation to thoroughly examine the parameters linked to physical activity in Chinese children and adolescents following the COVID-19 outbreak.

METHODS

The protocol was officially recorded and documented in the PROSPERO database in May 2024, with the assigned registration number CRD42024550080. This review adheres to the PRISMA guidelines (Moher et al., 2009).

Search strategy

We conducted the literature search using six electronic databases: PubMed, Web of Science, Scopus, Cochrane Library, SPORTDiscus, and ERIC. The search timeframe spanned from January 2019 to January 2024. The search strategy involved combinations of three keyword groups: (1) "*physical activ**" OR "*motor activ**" OR "*exercise**" OR "*physical fitness*" OR "*sport**" OR "*recreation**"; (2) "*adolescent**" OR "*teen**" OR "*youth**" OR "*young**" OR "*student**" OR "*child**" OR "*kid**"; (3) "*China*" OR "*Chinese*." We included the following MeSH terms in the PubMed search: "*physical activity*," "*exercise*," "*physical fitness*," "*sports*," "*adolescents*," "*students*," "*child*," and "*China*." We employed the '[All fields]' tag for all keywords in PubMed. We conducted topic-term searches in titles, abstracts, and keywords for all other databases.

Inclusion and exclusion criteria

Our review included studies that met the following criteria: (1) Research participants: healthy Chinese children and adolescents aged 3–18 years; (2) Exposures: factors that affect the involvement of children and adolescents in physical activity; (3) Outcomes: changes in physical activity behaviours; (4) Study designs: experimental studies; observational studies; as well as qualitative investigations; (5) Country: China; (6) Language: articles written in English.

The exclusion criteria included the following: (1) studies that did not address outcomes pertinent to physical activity; (2) the exclusion of participants with disabilities or health conditions that affect physical activity, such as heart disease; and (3) the study participants' residence outside of mainland China.

Data extraction

Methodological and outcome variables from each article were recorded using a standardized data extraction form. These variables encompassed author names, publication year, research focus, study design, sample size, age range, participant characteristics, physical activity measurement methods, physical activity levels, and critical findings.

Data synthesis

The extracted data indicate that the factors examined across various studies are diverse and inconsistent. Additionally, no studies employed identical measurement methods for the same factors, and the methods used to measure physical activity varied significantly. This inconsistency makes conducting a meta-analysis impossible. This review presents a cohesive summary of recurring themes and significant discoveries in the included research.

Quality assessment

The NIH Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies was used to evaluate the quality of each selected study. The instrument assesses studies based on 14 specific criteria. Each criterion was assigned a score of 1 if the response was 'yes'. Otherwise, it was assigned a value of 0 if the response was 'no', 'not relevant', 'not recorded', or 'cannot identify'. A study-specific global score was determined by aggregating the values from all categories. Each study was subject to independent evaluation by two reviewers (ML & CY).

RESULTS

Study identification

Fig. 1 shows the flow diagram for the selection of studies. Through keyword and reference searches, we identified a total of 10,269 articles. After removing duplicates, 7,585 articles remained. Screening based on titles and abstracts yielded 53 articles. Subsequently, after full-text reading and exclusion of articles with age differences, special populations, and irrelevant content, a total of 30 articles were finally included (An et al., 2021; Bao et al., 2023; Fan et al., 2019; F. Gao et al., 2022; W. Gao et al., 2022; Guo et al., 2022, 2023; Hong et al., 2020; C. Huang et al., 2023; W. Huang et al., 2021; X. Huang et al., 2021; Ke et al., 2022; Lei et al., 2020; Liang et al., 2022; J. Liu et al., 2022; Y. Liu et al., 2023; Lu et al., 2020; Lv & Wang, 2023; Lyu et al., 2019; Qiu et al., 2021; Qurban et al., 2019; Ren et al., 2020; Shi et al., 2022; Su et al., 2023; H. Wang et al., 2024; X. Wang & Jiang, 2023; Y. Wang et al., 2022; Xia et al., 2020; Zeng et al., 2022; Z. Zhou et al., 2023).

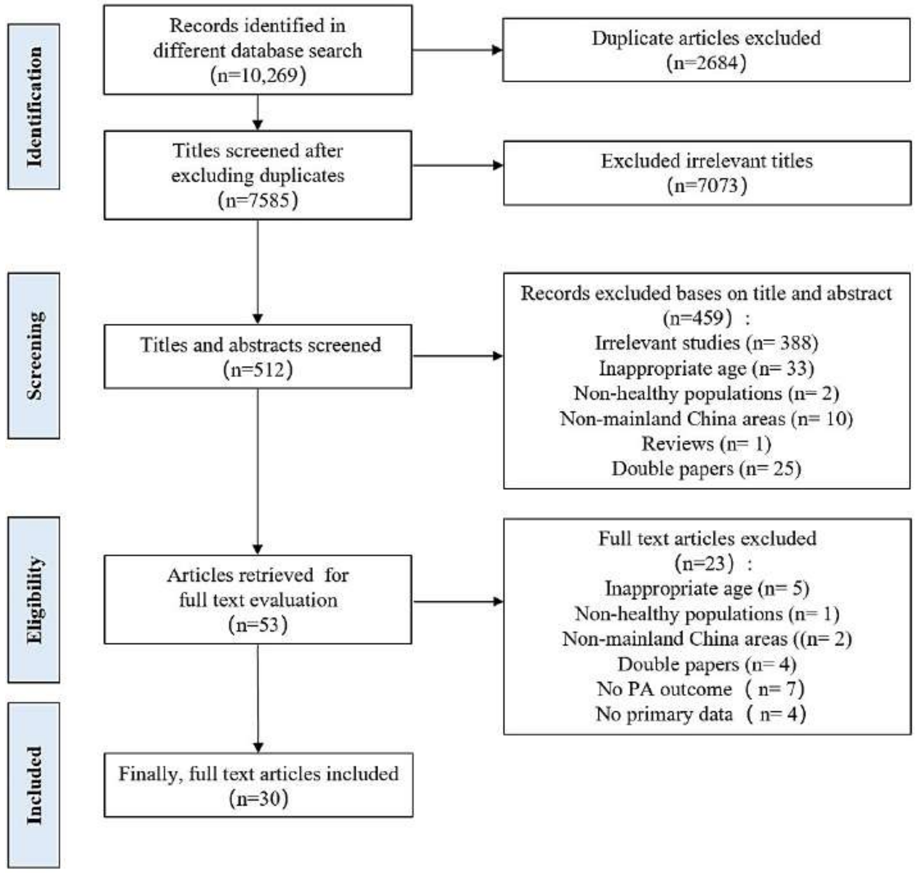

Figure 1. Flow diagram for selection of studies.

Basic characteristics of the included studies

Table 1 presents the fundamental characteristics of the 30 studies incorporated into this analysis. Four studies employed longitudinal designs. Three studies used objective tools to assess physical activity, while the remaining studies relied on self-reported measures. The sample sizes ranged from 255 to 93,600 individuals, with 23 studies (77%) having sample sizes greater than 1000. Thirteen studies exclusively recruited adolescents aged 11 to 19, four solely recruited preschool children aged 3 to 6, and thirteen enrolled children and adolescents aged 6 to 19.

Table 1 Main characteristics and main findings of the studies included in the review.

Author/ Year	Focus	Study design	Sample size	Sample characteristics	Measurement of PA	Main findings of study
An et al., 2021	Parental support	Cross-sectional	2670	Age: 7-15 years	Self-report questionnaire	Parental support behaviours are significantly associated with children's MVPA.
Bao et al., 2023	Urban parks	Cross-sectional	323	Age: 6-15 years	Self-report questionnaire	The landscape characteristics of urban parks are associated with children's physical activity, with semi open spaces, play facilities, and perceived safety showing a significant correlation.
Fan et al., 2019	Living arrangement	Cross-sectional	33213	Age:9-19years	Self-report questionnaire	Type of living arrangement was associated with the PA of youth in Shanghai, with no significant gender difference.

F. Gao et al., 2022	Region; urbanicity; family environment	Cross-sectional	41439	Age: 6–17 years	Self-report questionnaire	Children's outdoor time was significantly influenced by gender, age, urbanicity, region, annual total household expenditure, building environment, and meteorological conditions.
W. Gao et al., 2022	Region; parental support;	Cross-sectional	10967	Age: 3–6 years	Self-report questionnaire	Supportive family environment is positively associated with MVPA in Chinese preschool children.
Guo et al., 2023	Family structure	Cross-sectional	20000	Age: 12-18 years	Self-report questionnaire	Family structure has a significant impact on middle-school students' physical exercise.
Guo et al., 2022	Built environment	Longitudinal	517	Age: 14–17 years	Objective measure	Urban built environment significantly affected adolescents' weekend MVPA.
Hong et al., 2020	Parental support	Cross-sectional	61429	Age: 6–18 years	Self-report questionnaire	Various kinds of parental support have important effects on children and adolescents' MVPA, which varied by gender and grades.
C. Huang et al., 2023	Emotional/ behavioural problems	Cross-sectional	15071	Age: 13-17 years	Self-report questionnaire	Emotional and behavioural problems were negatively associated with PA, with sleep quality partially mediating the relationship between emotional and behavioural problems and PA.
W. Huang et al., 2021	Individual; School; Community	Longitudinal	1597	Age: 9–18 years	Self-report questionnaire	Both neighbourhood and school factors may affect students' MVPA, but school appears to play a more critical role in maintaining and promoting students' MVPA levels.
X. Huang et al., 2021	Built environment	Cross-sectional	749	Age: 7–12 years	Self-report questionnaire	Land-use mix around the school, the distance from home to school, and the distance to the nearest park are the top three important factors.
Ke et al., 2022	Socioeconomic status	Cross-sectional	2955	Age: 8–17 years	Self-report questionnaire	There are socioeconomic disparities in physical activity among Chinese children and adolescents.
Lei et al., 2020	Social networks	Cross-sectional	568	Age: 12–18 years	Self-report questionnaire	Adolescents' social networks positively influence their sports behaviour, with social efficacy acting as a mediator in this relationship.
Liang et al., 2022	Social Jetlag	Cross-sectional	3567	Mean age: 14.67 ± 1.72	Self-report questionnaire	Social jetlag negatively impacts adolescent participation in PA.
J. Liu et al., 2022	Social cognitive factors	Cross-sectional	3000	Age: 12–15 years	Self-report questionnaire	Social support had the greatest effect, self-regulation exerted a moderate effect, and self-efficacy and outcome expectations had a small effect on PA.
Y. Liu et al., 2023	Parental support; motivation	Longitudinal	2424	Age: 6-15 years	Self-report questionnaire	Intrinsic motivation and parental support can have a positive impact when physical activity levels change significantly.
Lu et al., 2020	Environment	Cross-sectional	980	Age: 3-6 years	Objective measure	Family structure and media exposure in the home maybe important factors in shaping preschoolers' PA patterns.
Lv & Wang, 2023	Built environment	Cross-sectional	2628	Age: 11-18 years	Self-report questionnaire	Built environment may be associated with leisure-time MVPA of Suzhou adolescents.

Qiu et al., 2021	Psychosocial Variables; Neighbourhood Environment	Cross-sectional	3833	Mean age: 14.7 ± 1.7	Self-report questionnaire	Psychosocial variables and availability of PA resources in the neighbourhood environment are positively related to out-of-school MVPA.
Qurban et al., 2019	Parental support	Cross-sectional	255	Age: 17 years	Self-report questionnaire	There were significant indirect effects of self-esteem and motivation on sports participation through parental support.
Ren et al., 2020	Social support; Exercise self-efficacy	Cross-sectional	2341	Age: 12-17 years	Self-report questionnaire	Exercise self-efficacy and social support are significant and positive predictors of PA in Chinese adolescents.
Shi et al., 2022	Family structure	Cross-sectional	4800	Age: 9–17 years	Self-report questionnaire	The PA levels of most children and adolescents were insufficient in western China and were affected by family structure and parental activity.
Su et al., 2023	Significant others	Cross-sectional	2484	Age: 11-18 years	Self-report questionnaire	The social influences of parents, physical education teachers, and peers were equally important to students' intention to take part in leisure-time PA.
H. Wang et al., 2024	School physical education	Cross-sectional	3708	Age: 6-17 years	Self-report questionnaire	School PE participation and duration increased out-of-school PA participation and duration, respectively.
X. Wang & Jiang, 2023	Gender; Parental support	Cross-sectional	1308	Age: 3–6 years	Self-report questionnaire	Parents' support on sports, and sports grounds near their homes were the main factors affecting the lack of MVPA time for urban migrant children.
Y. Wang et al., 2022	Community environment	Cross-sectional	471	Age: 3-6 years	Objective measure	Public activity facilities, the community transportation environment, and community personal safety are important factors.
Lyu et al., 2019	Family structure	Cross-sectional	93600	Age: 6-16 years	Self-report questionnaire	The more stable the family structure is, the better the family sports atmosphere will be.
Zeng et al., 2022	Family environment	Cross-sectional	3738	Age: 10-19 years	Self-report questionnaire	Parental support was not only positively directly but also indirectly associated with MVPA in Chinese boys through the home environment and the autonomous motivation of adolescents.
Z. Zhou et al., 2023	Peer effect	Longitudinal	7843	Seventh-grade junior high school students	Self-report questionnaire	The peer effect is causally related to adolescents' physical activity.
Xia et al., 2020	Socioeconomic status	Cross-sectional	9365	Main age: 13.56 years	Self-report questionnaire	Parental SES is directly linked to junior school students' sports participation and indirectly influences it through classmate support and parental involvement.

Note. PA: physical activity; MVPA: moderate to vigorous physical activity; SES: socioeconomic status.

Study quality assessment

The average score of the studies included in the analysis was 8 out of 14 points, ranging from 6 to 13. All studies explicitly articulated their research questions and objectives and clearly defined the study population, achieving participant recruitment rates of 50% or greater. All studies recruited participants from similar groups, applying consistent criteria for inclusion and exclusion to all individuals. Five studies provided a power analysis for the sample size. Four studies measured exposure variables before outcome assessment. Six studies conducted long-term follow-ups to examine associations between exposure and outcomes. Twenty studies examined different levels of exposure related to outcomes. All studies employed effective and standardized exposure measurements. During the study period, only five studies carried out multiple exposure measurements. Five studies utilized efficacious and dependable outcome assessments. None of the studies had outcome assessors blinded to participants' exposure status. Additionally, two studies reported attrition rates exceeding 20%. All studies included statistical measurements and adjustments for critical potential confounding variables.

Main findings

Table 1 also summarizes the potential correlates of physical activity among children and adolescents in China. The variables included in the studies primarily relate to demographics, individual, family, neighbourhood environment, and school. The key variables are age, gender, urbanization, motivation, self-efficacy, peer support, parental support, family sports environment, family structure, socioeconomic status, community sports facilities, community aesthetics, neighbourhood safety, teacher support, and school physical education, totalling fifteen variables.

Regarding demographic characteristics, studies consistently show that boys have significantly higher physical activity participation rates than girls. Inactivity also increases as age increases, regardless of gender. The relationship between urbanization and physical activity varies across age groups. Studies for preschool children show that urban children have higher compliance rates with moderate to vigorous physical activity recommendations than rural children (W. Gao et al., 2022). However, for school-aged children, rural children tend to have higher physical activity levels (Fan et al., 2019; F. Gao et al., 2022).

In terms of personal factors, motivation and self-efficacy have shown significant correlations with physical activity (J. Liu et al., 2022; Y. Liu et al., 2023; Qiu et al., 2021; Qurban et al., 2019; Ren et al., 2020; Zeng et al., 2022). Additionally, factors such as social interactions (Lei et al., 2020), lifestyle habits (Liang et al., 2022) and psychological status(C. Huang et al., 2023) are also related to physical activity. Moreover, studies consistently indicate that peer support has a significantly positive impact on physical activity among children and adolescents. (W. Huang et al., 2021; Qiu et al., 2021; Su et al., 2023; Z. Zhou et al., 2023)

Regarding family factors, parental support significantly correlates with physical activity (An et al., 2021; W. Gao et al., 2022; Guo et al., 2023; Hong et al., 2020; W. Huang et al., 2021; Y. Liu et al., 2023; Lu et al., 2020; Qiu et al., 2021; Qurban et al., 2019; Shi et al., 2022; Su et al., 2023; X. Wang & Jiang, 2023; Xia et al., 2020; Zeng et al., 2022), with the frequency of parental exercise showing the strongest correlation (W. Gao et al., 2022; Guo et al., 2023; W. Huang et al., 2021; Y. Liu et al., 2023). The diversity of home sports facilities is positively correlated with physical activity (W. Gao et al., 2022; Zeng et al., 2022), whereas the presence of media devices, such as televisions or computers in bedrooms, is positively correlated with prolonged sedentary behaviour in preschool children (Lu et al., 2020). Additionally, socioeconomic status and family structure are associated with physical activity frequency, with children and adolescents from higher socioeconomic backgrounds and intact families generally participating more in physical activity (Guo et al., 2023; Ke et al., 2022; Shi et al., 2022; Xia et al., 2020).

For the neighbourhood environment, studies reveal a significant correlation between the built environment and physical activity among children and adolescents. Community aesthetics, sports facilities, and neighbourhood safety are the environmental factors most closely associated with physical activity (Bao et al., 2023; Guo et al., 2022; X. Huang et al., 2021; Lu et al., 2020; Lv & Wang, 2023; X. Wang & Jiang, 2023).

Lastly, three studies examined the relationship between school characteristics and physical activity, suggesting that support from physical education teachers is positively associated with adolescents' extracurricular physical activity (Su et al., 2023). Moreover, children and adolescents who participate in school physical education are more likely to engage in extracurricular physical activity (W. Huang et al., 2021; H. Wang et al., 2024).

DISCUSSION

The review examined scientific evidence on the correlates of physical activity among children and adolescents in China over the past five years, encompassing a total of 30 studies. The findings suggest that age, gender, urbanization, motivation, self-efficacy, peer support, parental support, family sports environment, family structure, socioeconomic status, community sports facilities, community aesthetics, neighbourhood safety, teacher support, and school physical education are associated with physical activity.

The review found a link between gender and physical activity, consistent with other studies conducted in many countries, including China (Lu et al., 2017; Shao & Zhou, 2023). Furthermore, age seems to significantly influence the formation of physical activity patterns. The study revealed that irrespective of gender, physical inactivity levels tend to rise as individuals grow older. Studies conducted in other countries have found similar results, with an Israeli study observing a substantial inverse relationship between physical activity and age (Zach et al., 2012). Similarly, previous systematic reviews support this view (Craggs et al., 2011). In China, most adolescents attend middle or high school, facing immense academic pressure that may leave them with insufficient time and energy to engage in physical activities. Additionally, before reaching middle school, many Chinese children often participate in various sports interest classes. However, upon entering middle school, many parents may require their children to abandon these interest classes to focus on studying for the high school entrance examination. This could also be a contributing factor to the inverse correlation between age and physical activity.

The findings of this review indicate a direct association between motivation and physical activity, with intrinsic motivation showing the strongest link to physical activity. Studies from other nations have also confirmed this discovery. A European study serves as an example, demonstrating how autonomous motivation can mediate the influence of environmental factors, like perceived autonomy support from friends and parents, on physical activity. This, in turn, affects the beginning and ongoing nature of physical activity (Rutten et al., 2013). However, the key factors that stimulate intrinsic motivation are poorly understood (Pannekoek et al., 2013). Future research should focus on understanding which factors are associated with children and adolescents' motivation to participate in physical activity and which factors are most amenable to change. This will provide valuable insights for designing intervention measures to enhance motivation for participating in physical activities and ultimately promote physical activity engagement.

Adolescence is a period during which individuals gradually gain independence, and social support from peers and friends becomes increasingly important. This review identified a clear correlation between peer support and physical activity in adolescents. Both peer support and dedicated time for exercising with peers had a beneficial impact on teenagers' physical activity (W. Huang et al., 2021; Qiu et al., 2021; Su et al., 2023; Xia et al., 2020; Z. Zhou et al., 2023). Additionally, the research revealed that adolescents with more extensive and more interconnected social networks tend to participate in more excellent physical activity (Lei et al., 2020). Their greater susceptibility to influence and support from friends or peers may increase their frequency of participation in physical activities. Prior studies have similarly found a positive correlation between friend support and physical activity in both early and late adolescence, although the magnitude of this impact was small (Laird et al., 2016; Mendonça et al., 2014). Research investigating the association between peer support and physical activity remains limited, with most studies conducted in developed countries (Mendonça et al., 2014). Future research in China should expand on peer influence, investigate the significance of peer social networks, and consider the role of peer influence in children.

Through our investigation of the correlation between family characteristics and physical activity, we have shown that parental support, parental physical activity frequency, and family structure demonstrate the most significant connections with physical activity. Our findings diverge from studies carried out in other nations. Other countries' previous reviews show a slight beneficial association between parental support and physical activity in teenagers (Laird et al., 2016; Mendonça et al., 2014). Moreover, evidence of the benefits of parents participating in physical activities with their children and serving as role models is limited (Yao & Rhodes, 2015). However, our research findings demonstrate a notable correlation between parental backing and physical activity habits in Chinese kids and teenagers (Guo et al., 2023; Hong et al., 2020). Furthermore, the frequency of physical activity among parents significantly influences Chinese teenagers' physical activity (Hong et al., 2020; W. Huang et al., 2021). Moreover, our review has revealed a substantial association between family composition and physical activity levels (Guo et al., 2023; Lyu et al., 2019). Children and adolescents from intact homes typically have greater physical activity levels than those from alternative family configurations. Those living with both parents are typically more physically active than those living with a single parent or grandparents. These findings suggest that, in the Chinese context, parental support and involvement are crucial in boosting physical activity for young people.

Our investigation revealed a consistent and favourable relationship between socioeconomic status and physical activity. This finding deviates to some extent from prior studies conducted in China (Lu et al., 2017). A subsequent study found that this association may vary depending on specific circumstances, with a negative correlation between socioeconomic status and sedentary behaviours in affluent nations and a direct relationship in less affluent nations (Kandola et al., 2020). One possible explanation is the continuous increase in China's urbanization rate over the past few decades (from less than 30% in 1990 to 66% in 2023) (National Bureau of Statistics of China, 2024). Consequently, there has been a notable surge in the population of children and adolescents residing in urban regions. Urban children and adolescents enjoy greater accessibility to a wide range of sports facilities and activity resources, which enhances their chances of engaging in physical activities. This enhanced accessibility amplifies the correlation between socioeconomic position and physical activity.

Furthermore, we discovered a correlation between the indoor surroundings of households and physical activity. Sporting facilities at home may encourage greater participation in physical activities (Lu et al., 2020), while electronic media devices may lead to spending more time on recreational screens, thus reducing physical activity time (Lu et al., 2020; Zeng et al., 2022). This result aligns with studies undertaken in other nations (Fairclough, 2021; Sirard et al., 2010). However, there is a dearth of research on the influence of one's home's physical environment on physical activity levels. Furthermore, most existing research on this subject has primarily focused on family social aspects, such as parental support and family structure.

In recent years, as urbanization has rapidly advanced and the urban population in China has dramatically increased, there has been a growing concern about the correlation between built surroundings and activity levels. Our review uncovered various built-environment characteristics that are associated with physical activity. These factors include neighbourhood safety, community landscapes (such as green areas), and community sports facilities. These findings are broadly consistent with previous research. However, in China, neighbourhood safety is of particular concern to both parents and adolescents, and it has a stronger association compared to other factors (Bao et al., 2023; Lv & Wang, 2023). Currently, cross-sectional research offers insights into the relationship between urban settings and physical activity (Ding et al., 2020). Subsequent research should employ longitudinal designs and consider the impact of environmental interventions on physical activity within controlled experimental settings.

Traditionally, schools have been regarded as vital settings for fostering the well-being and growth of children and teenagers. Nevertheless, efforts to promote physical activity within schools have frequently failed to achieve desired outcomes (Borde et al., 2017; Dobbins et al., 2013; Love et al., 2019). Our research indicates that the presence of physical education teacher support and a wide range of school physical activities are correlated with more significant amounts of physical activity (W. Huang et al., 2021; Su et al., 2023; H. Wang et al., 2024). However, this finding is based on only three relevant cross-sectional studies, raising concerns about potential biases in the results. Furthermore, prior studies have shown that there is no correlation between the amount of assistance provided by teachers and the amount of physical activity among adolescents (Laird et al., 2016; Mendonça et al., 2014; Morton et al., 2016; Y. Zhou & Wang, 2019). At present, there is a lack of definitive findings identifying the specific school-related factors that impact physical activity levels. Current research primarily focuses on evaluating the efficacy of physical activity treatments implemented in schools, with few studies investigating school-related characteristics associated with physical activity. Future research should include broader school factors, including school policies, culture, and physical environments, to offer targeted guidance and enhance the implementation and effectiveness of school-based physical activity interventions.

This review has several limitations. Firstly, all the included studies were observational, meaning that without experimental designs, we cannot make causal inferences about the influence of various factors on physical activity; the observed relationships are merely correlational. Secondly, none of the studies provided quantitative estimates focusing on identical factors and physical activity measures, preventing a meta-analysis. Although the review focuses on the latest developments in factors affecting physical activity among Chinese children and adolescents, the search for relevant literature was limited to English-language publications from the last five years. This restriction may have resulted in incomplete information and inadequate evidence.

CONCLUSION

This review examines various factors linked to the physical activity behaviours of Chinese children and adolescents, including gender, age, urbanization, motivation, self-efficacy, peer support, parental support, parental engagement in physical activities, family structure, socioeconomic status, family exercise equipment, neighbourhood safety, community aesthetics, and the accessibility of community sports amenities. Notably, in the Chinese context, parental support, parental participation in physical activities, family structure, and neighbourhood safety have stronger associations with children and adolescents' physical activity behaviours. Moreover, the results suggest insufficient definitive data about the school-related factors linked to physical activity. In order to provide targeted guidance, future research should consider a broader range of school factors, including policies, culture, and the physical environment.

AUTHOR CONTRIBUTIONS

Meng Liu led the design and implementation of the study, conducted the literature search, screening, and data analysis, and drafted the manuscript. Abu Saad Hazizi supervised the research process, provided methodological guidance, participated in literature screening and analysis, and conducted a comprehensive review and revision of the manuscript. Kim Geok Soh contributed to methodological guidance and oversaw the research process. Chuang Yuan assisted with the literature search and screening and participated in portions of the data processing. Guangtao Ren also assisted with the literature search and screening and contributed to data processing.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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REVIEW ARTICLE

Effect of stroboscopic visual training in athletes: A systematic review

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ABSTRACT

Background : Visual abilities and motor performance are the key factor in athletes to improve their performance. One emerging technology to enhance athletes' visuomotor and cognitive abilities is SVT. This paper aims to show how SVT can be used as an intervention technique in athletics to enhance athletes' performance. Any research that examined the use of strobe glasses as a training aid for physically fit athletes was taken into consideration for this evaluation. Objectives : The purpose of this study is to investigate the impact of stroboscopic visual training on athletes. Methods: In January 2024, searches were conducted using a variety of databases, including PubMed, Scopus, Google Scholar, Springer, ProQuest databases. Screening publications that included strobe glasses as a training aid was done by two independent reviewers. 13 of the 25 full-text articles that were evaluated for inclusion and exclusion satisfied the requirements. Results: The results of the SVT intervention were: enhanced visual and visuomotor function; improved reaction time; enhanced eye-hand coordination; enhanced perceptual skills; enhanced short-term memory; enhanced central visual field motion; enhanced anticipatory timing; no improvement in peripheral field motion; some athletes reported feeling mentally exhausted and unable to identify colours. Conclusions: More research is necessary to establish the ideal strobe dosage and administration since there are no established guidelines for SVT intervention settings, duration, and outcomes in athletes. With future recommendations to athletes and coaches to incorporate SVT as part of sports training to improve their on-field performance, this review outlines the advantages of SVT intervention in athletes as well as the current research gaps addressing the usage of SVT.
Keywords: Strobe, Stroboscopic visual training, Athletes.

Cite this article as:
Jothi, S., Dhakshinamoorthy, J., & Kothandaraman, K. (2025). Effect of stroboscopic visual training in athletes: A systematic review. *Journal of Human Sport and Exercise, 20*(2), 562-573. https://doi.org/10.55860/vm1j3k88

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Submitted for publication December 09, 2024.
Accepted for publication January 21, 2025.
Published February 10, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/vm1j3k88

INTRODUCTION

Sports vision training (SVT) and other performance training methodologies like strength, conditioning, speed and agility, nutrition, and sports psychology have a common objective of translating functional benefits to athletic performance. The relevant queries are whether it is possible to train one's visual abilities and whether an athlete's increased ability to see improves their performance in sports. Training is a possibility for many of the visual characteristics that have been found to be significant in sports.

The development of visual training devices was encouraged by the growing awareness of the role that visual and visuomotor talents play in determining performance in sports (Hülsdünker et al 2021).An increasing amount of study is looking into how using visual training interventions might improve athletes' performance (Ellison et al 2020).Generally speaking, the idea behind stroboscopic training is an activity that uses sporadic visual stimuli to increase the strain on visuomotor processing and improve performance under normal vision settings (Zwierko et al 2024).

Shutter glasses, sometimes referred to as stroboscopic eyewear, are becoming more and more common in sports-specific training because they enable athletes to practice in certain visual environments (Zwierko et al 2024). One example of contemporary technology that has helped with multimodal integration is strobe glasses (Vasile et al 2023). Products like Platino glasses, Nike SPARQ vapor strobes, and, more recently, Senaptec stroboscopic glasses made it easier to evaluate temporal occlusion and stroboscopic vision in practical contexts (Dunton et al2020).

A type of cognitive motor training known as "*strobe training*" involves performing motor tasks in dimly lit environments on occasion (Vasile et al 2023). Enhancing neuro visual processing vision training is a method that can be used to enhance athletic performance and reduce injury risk. This method incorporates visual exercise into a structured sports environment program (Sudesan et al 2023).

Top athletes in training and competition need to have excellent eyesight and perception in addition to a high degree of attention (Jendrusch et al 2023). The key to achieving peak athletic performance is seeing and then generating the proper motor response (Patrícia et al 2020). In order to prevent injuries, vision training is a simple and effective addition to regular pre-season training regimens (Clark et al 2020).

Generally speaking, the concept behind stroboscopic training is an exercise consisting of sporadic visual stimuli that increase the workload on the visuomotor system, improving performance under normal vision settings. The goal of many vision performance assessments and training programs for enhancement is to evaluate and enhance the overall processing of visual information. The majority of enhancement training programs aim to improve the visual abilities necessary for good sports performance in order to influence the perceptual process.

The main objective of visual improvement training programs is to prime the athlete's perception and effector mechanisms for future information while simultaneously focusing their ability to handle more information in less time. In the end, this increases the decision mechanism's speed and effectiveness, which is further improved by processes that offer feedback on visual attention and promote the formation and use of mental images. Even if there are still a lot of unsolved problems about how visual enhancement training affects sports performance.

The study's goal is to compile a list of every peer-reviewed study that looked into using SVT to enhance athletic performance. The review sought to: (1) Present the SVT results; and (2) Offer recommendations for further study

METHODS

Search strategy

A preliminary search was conducted in January 2024 across five databases—PubMed, Scopus, Springer, ProQuest, Google Scholar —using the search term ("*KEY WORDS: STROBOSCOPIC VISUAL TRAINING AND SPORTS*."). The scope of the search was restricted to complete English-language journal articles published between January 2010 to January 2024.The reviewer (SJ) removed duplicates and did a screen test after two separate reviewers (VS and SJ) examined the entire articles. If the study's eligibility for review was unclear from the title, full text articles were eliminated.

Inclusion and exclusion criteria

Articles that employed stroboscopic visual training as a form of intervention were included. This study only included research articles with human subjects. Articles covered the effects of athletes' visual performance and whether or not strobe glasses were used during the training phase to induce intermittent vision. Any sport that uses stroboscopic visual training is included. Included were studies that looked at how stroboscopic visual training affected task performance right away. Excluded were studies that examined the effects of SVT in clinical patients rather than in healthy individuals, or that included SVT as a component of multiple visual training. SVT related abstracts, discussion papers, and review papers were not included.

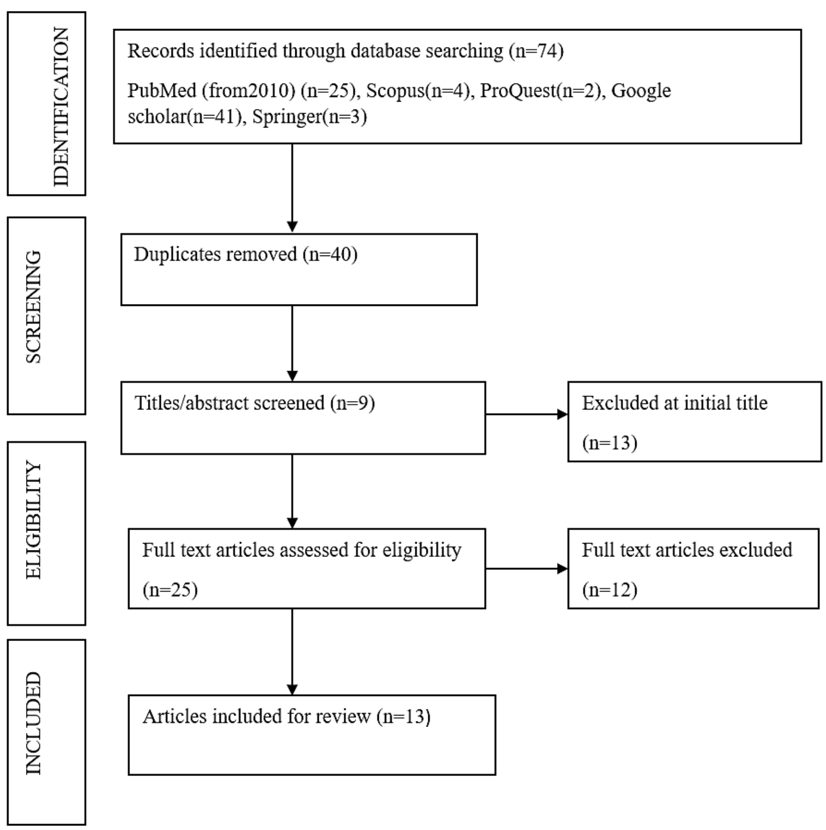

Figure 1. Prisma search strategy (search updated January 2024).

Data extraction

A second reviewer (VS) verified the data entered after the first reviewer (SJ) extracted and synthesized the data into a tabular format (Table 1). Details such as the name of the participant, the characteristics, the eligibility requirements, the design, and the purpose of the study. Table 2 contained the participant group, kind of eyeglasses, study protocols, flash settings, and important findings.

Table 1. Participant characteristics, sports, inclusion and exclusion criteria, design and aim of the reviewed studies.

Author	Participants	Sports	Inclusion criteria	Exclusion criteria	Study design and aim
Zwierko et al. (2023)	Initially 58 participants were recruited 50 volleyball athlete's participants (26 males,24 females) Age 16-18 years SVT group(n = 25) Control group(n = 25)	Volleyball	a) volleyball training on a regular basis, at least 5 days a week, and (b) participating in official volleyball federation competitions during the season	H/O epilepsy, migraine, or injury.	Pretest and post-test study Effect of SVT on visual, visuomotor and reactive agility.
Hülsdünker et al. (2021): Part 1	45 young badminton athletes participated 13 excluded illness (n = 5), missing data (n = 2), or insufficient training time (n = 6). 32 participants (21 male, 11 females, 27 left handed, 5 right handed; age, 13.7 ± 1.3 yr; height, 166.2 ± 10.9 cm; weight, 54.5 ± 11.4 kg)	Badminton	Competitive at national level badminton	H/O epilepsy, migraine, or neurological or psychiatric disorders	Longitudinal Pretest and post-test study Long term and short-term effect of SVT on reaction time and on-court performance.
Ellison et al (2020)	62 athletes a strobe group (SG; n = 31, age 20.82 ± 1.54 yrs.), or control group (CG; n = 31, age 21.34 ± 4.27 yrs.)	Not mentioned	Novice to eye hand coordination	H/O epilepsy	Pretest and post-test Effect of SVT on eye hand coordination.
Luke Wilkins et al. (2018)	6 elite young football goalkeeper's participants Experimental group-3 Control group-3	Football	Not recorded	Not recorded	Pilot pretest and post-test study Effect of SVT on visual and perceptual skills.
Palmer et al. (2022)	61 youth soccer players were recruited (aged 11.2 ± 1.3 years) 36 participants	soccer	Not recorded	Not recorded	Pretest and post-test study Effect of SVT on dribbling performance of fast and slow dribbler.
Appelbaum et al. (2012)	84 participants	Soccer, basketball	Not recorded	H/O seizures, migraines, or light sensitivity	Pretest and post-test study Effect of SVT on visual memory
Teresa Zwierkoet al. (2024)	22 highly experienced male handball players participants, including 20 right-handed and two left-handed, with a mean age of 24.59 years (±5.4)	Handball	Not recorded	Not recorded	Pretest and post-test study Effect of SVT on conductivity of the visual pathway specifically related to their visual processing of retinal location and viewing conditions
Antonia Ioana Vasile et al. (2023)	9 climbers with ages between 13 and 19 years (M = 16.59; SD = 2.00), of which 4 male and 5 female.	climbing	1.age over 12 years old and lower than 20 years old 2. a frequency of at least three training sessions per week with their head coach 3. achieving at least one red-point lead route higher than 7a+ measured of French scale in the last year before enrolling into the study 4. active participation in national and international competitions and federal training camps for juniors.	Not recorded	Pretest and post-test study Formulating preliminary model of training climber with strobe glasses explaining time of training, methods, materials, dosing, intensity, walls to use. We also explained the benefits of this method of training, disadvantages and adaptability.
Sudesan J. et al (2022)	30 participants ST group-15 Control group-15 Age 19 -25	Football Volleyball cricket	Not recorded	Not recorded	Acute pretest and post-test study Acute effect of SVT on visuomotor skills

Jendrusch et al (2023)	22 tennis players participants (18m, 4f, mean age = 23.6, SD = ±2.7 years)	Tennis	Not recorded	Not recorded	Pretest and post-test study Analyses the effect of shutter glass on (image-)frequency or "*duty ratio*" (dark phase percentage) on target stroke accuracy in tennis
Appelbaum et al (2011)	157 participants University students and athletes SG-16 CG-15	Athletes	Not recorded	H/O Seizures Migraine Sensitivity to light	Pretest and post-test study Effect of SVT on Motion sensitivity peripheral vision and dual task attention Sustained attention
Smith and Mitroff (2012	30 athletes SG-15(Age 20 -27 years) CG-15(Age 20 -29 years) (Strobe: M = 22.80, SD = 2.11; Control: M = 23.60, SD = 2.82; t(28) = 0.88, *p* = .387)	Athletes	Not recorded	Not recorded	Pretest and post-test study Effect of SVT on anticipatory timing
Hülsdünkeret al.(2021): Part 2	45 young badminton athletes participated 13 excluded illness (n = 5), missing data (n = 2), or insufficient training time (n = 6). 32 participants (21 male, 11 females, 27 left handed, 5 right handed; age, 13.7 ± 1.3 yr; height, 166.2 ± 10.9 cm; weight, 54.5 ± 11.4 kg)	Badminton	Competitive at national level badminton	H/O epilepsy, migraine, or neurological or psychiatric disorders	Longitudinal Pretest and post-test study Effect of SVT on reaction time

Table 2. Types of strobes, strobe settings, frequency and duration of the training total strobe time, intervention and key findings.

Author	**Types of strobes**	**Strobe settings**	**Frequency/Duration of training**	**Total strobe time(Mins)**	**Intervention/Task**	**Key findings**
Zweirkoetal. (2023)	Senaptec strobe	Modulated frequency 15-9 Hz (duty ratio 50%-70%)	6 weeks 18 sessions × 25-40 mins	450-540 mins	Wall passing drills, partner passing drills, passing rotation drills.	Improved visual and visuomotor function
Hulsdunker et al (2021) part 1	Senaptec strobe	Preprogrammed frequency (15hz-8hz) Duty ratio :50%-70%	10weeks 10sessions ×10-15 mins	100-150 mins	Drive drills, net drive drills, ball machine drills	Improved visuomotor reaction speed
Ellison et al (2020)	Nike vapor strobe eyewear	Fixed frequency of level 3 (4hz)	Single session ×7-8min	7-8min	Sports vision trainer light board	Improved eye hand coordination performance
Luke Wilkins et al (2018)	Senaptec strobe	Modulated frequency of level 1-8(6hz-1hz)	7weeks 14 sessions× 45mins and 1× 5 mins	635 mins	Catching drills using tennis ball and goalkeeper specific drills using a football	Improved visual and perceptual skills
Palmer et al (2022)	Nike vapor strobe eyewear	Modulated frequency of level 3 -7(4hz-1.33hz)	4weeks 4 sessions × 20 mins	80 mins	Dribbling exercise	No persistent changes seen in soccer in situ dribbling performance
Appelbaum et al (2012)	Nike vapor strobe eyewear	In lab: Level 1-6 Training: Level 2-4	In lab: 2 sessions ×27min Varsity soccer: 6or 7 sessions ×15-45 mins Varsity basketball: 5or 6 sessions × 15-40 mins	54-315 mins	Catch, agility and ball handling drills	Improved short term memory and retention short term memory capacity
Teresa Zweirko et al (2024)	Senaptec strobe	Modulated frequency 5hz-9 Hz (50%-70%)	6 weeks 18 sessions	Not mentioned	Ball catch drills partner passing drills, handball specific passing drills	Improved effect on early visual processing in short term
Antonia Ioanavasile et al (2023)	Senaptec strobe	Fixed frequency of level 1 and 2	6 sessions × 2 hours	12 hours	Climbing on bouldering, lead, spray wall, and moon board	Improved motor-cognitive skills

Sudesan J. et al (2022)	Senaptec strobe	Modulated frequency of level 1-8	Single session × 7-8 mins	7-8 mins	Catching drills and specialist drills with a football for cricket and volleyball players	Improved visual response time
Jendrusch et al (2024)	Nike vapor strobe eyewear	Preprogrammed frequency of level 2,5,and 8	Single session	Not mentioned	Striking balls dispensed from a tennis ball machine	Improved the precision of the eye hand coordination in tennis
Appelbaum et al (2011)	Nike vapor strobe eyewear	Modulated frequency of level 1-6	In lab: 2or 4 sessions × 27 min Club ultimate Frisbee: 4 sessions × 20 -25 mins Varsity football: 9or10 sessions ×15- 30 mins	54-300 mins	Catch drills, Frisbee practice speed and agility drills	Improvement in central visual field motion
Smith and Mitroff (2012)	Nike vapor strobe eyewear	Fixed frequency of level 3 (4hz)	Single session ×5-7mins	5-7mins	Anticipation training	Improved anticipatory training
Hulsdunker et al (2021) Part -2	Senaptec strobe	Modulated frequency 15hz-8hz (Duty ratio 50%-70%)	10 weeks 10 sessions ×10-15 mins	100-150mins	Badminton drills	Improved visual perception skills

RESULTS

The evidence base

A total of 74 papers were produced using the search method. We eliminated about forty duplicate articles from the search.34 articles of relevance were found after the first reviewer (SJ) did an initial scan of titles and abstracts. Nine publications were eliminated after an abstract assessment. The first and second reviewers (SJ and VS) have examined 25 full-text publications. Twelve papers were eliminated on the grounds of exclusion. There was agreement to include 13 articles for the study committee to review.

Study population

Participants

The majority of participants were in their late teens or early twenties and were recruited through professional or elite sports teams or their university cohorts. Two studies looked at how SVT affected athletes right away (Sudesan et al 2023, Smith et al 2012). With the exception 1 study that exclusively enrolled male participants (Zwierko et al 2024), 5 studies were recruited all gender (Zwierko et al 2023, Hülsdünker et al 2021, Vasile et al 2023, Jendrusch et al 2023, Hülsdünker et al 2021). 7 studies did not report any particular gender traits (Ellison et al 2020, Wilkins et al 2018, Palmer et al 2024, Appelbaum et al 2012, Sudesan et al 2023, Appelbaum et al 2011, Smith et al 2012) (Table 1).

Eligibility criteria

Seven studies did not list any exclusion standards for their subjects (Wilkins et al 2018, Palmer et al 2024, Zwierko et al 2024, Vasile et al 2023, Sudesan et al 2023, Jendrusch et al 2023, Smith et al 2012). The remaining six studies listed migraines, a history of neurological disorders, and/or seizures/epilepsy as reasons why participants should not participate (Zwierko et al 2023, Hülsdünker et al 2021, Ellison et al 2020, Appelbaum et al 2012, Appelbaum et al 2011, Hülsdünker et al 2021) (Table 1).

Cohort structure

Sample size: The number of participants ranged from 6 (Wilkins et al 2020) in pilot research to 157(Appelbaum et al 2011) in the first study conducted by Appelbaum and colleagues, indicating a significant variation in participant sample sizes between the studies.

Control groups: A control group was a part of all 13 trials.

Study protocols

Stroboscopic devices

Throughout the 13 trials, two distinct brands of eyewear devices that are available for purchase were utilized to provide stroboscopic visual disruption (Table 2). The Nike Vapor Strobe (Ellison et al 2020, Palmer et al 2024, Appelbaum et al 2012, Jendrusch et al 2023, Appelbaum et al 2011, Smithet al 2012) (n = 6) and the more recent Senaptec strobe (Zwierko et al 2023, Hülsdünker et al 2021, Wilkins et al 2018, Zwierko et al 2024, Vasile et al 2023, Sudesan et al 2023, Hülsdünker et al 2021) (n = 7) was the most often used devices in the studies. Nike is located in Beaverton, Oregon.

Strobe settings

Out of the 13 research, 3 studies conducted their stroboscopic training at a single fixed frequency (Ellison et al 2020,8, Smith et al 2012),7 studies had modulated frequency (Zwierko et al 2023, Wilkins et al 2018, Palmer et al 2024, Zwierko et al 2024, Sudesan et al 2023, Appelbaum et al 2011, Hülsdünker et al 2021) and 2 studies had pre-programmed frequency (Hülsdünker et al 2021, Jendrusch et al 2023).

Frequency and duration of interventions

SVT sessions ranged in duration from five minutes (Smith et al 2012) to a maximum of 12 hours (Vasile et al 2023) in different trials. The remaining studies (n = 11) offered numerous SVT sessions for up to 10 weeks with 50 minutes and 2 studies didn't mention any time duration (Zwierko et al 2024, Jendrusch et al 2023) (Table 2). Additionally, there was a notable variation in the length of training across studies.

Training intervention

When performing physical activities like wall passing drills, passing drills (Zwierko et al 2023, Zwierko et al 2024), drive drills, ball machine drills, catching drills (Wilkins et al 2018, Appelbaum et al 2012, Zwierko et al 2024, Sudesan et al 2023, Appelbaum et al 2011) and goalkeeper specific drills, dribbling exercise (Palmer et al 2024), climbing on bouldering (Vasile et al 2023) were done wearing strobe glasses.

Post training test points

Depicts those two studies (Sudesan et al 2023, Smith et al 2012) were conducted immediate post-test following training in all of the evaluated research, and 11 of those studies also recorded retention test data with delays of 10, minutes, 24 hours, 10 days, 4 weeks, and 6 weeks.

Outcome measures

Most research (n = 7) examined the relationship between SVT results and one or more specific visual abilities, such as visual processing, visual memory, or reaction time or eye hand coordination (Zwierko et al 2023, Hülsdünker et al 2021, Ellison et al 2020, Wilkins et al 2018,7, Sudesan et al 2023, Jendrusch et al 2023, Hülsdünker et al 2021). One study showed that SVT improved motor cognitive skills (Vasile et al 2023). Study by Smith and Mitroff explained acute SVT leads to improved anticipatory timing in athletes (Smith et al 2012). Hulsdunker and colleagues identified modulations in the participants' visuomotor performance and visual perception speed using neurophysiologic research. Improvement in short-term memory retention (Appelbaum et al 2012). SVT had a small impact on P100 amplitude and reduced the P100 implicit time for the dominant eye, especially in extra foveal vision. Additionally, under binocular seeing conditions, the stroboscopic intervention had a positive impact on extra foveal vision (Zwierko et al 2024). Focused attention, distributed attention, memory, visualization, selecting the best climbing pace, body placement on the wall, sensory reorientation on proprioception, central and peripheral vision, and intersegmental coordination were indicated as the competencies of the training approach. Athletes report feeling mentally exhausted, dizzy, and unable to discern colour following SVT (Vasile et al 2023). The study demonstrated that increasing the load of strobe frequency reduced target hit precision and eye-hand coordination in tennis players. It also established the necessary conditions for organizing and arranging stroboscopic visual training with shutter glasses and then carrying it out methodically over an extended length of time (Jendrusch et al 2023). Greater visual information in the central visual area and no change in the peripheral attention task were observed (Appelbaum et al 2011).

Interpretation of outcomes

A number of distinct visual and motor performance outcomes, including central field motion sensitivity, short-term memory capacity (Appelbaum et al 2012), processing speed, eye-hand coordination (Ellison et al 2020, Smith et al 2012) anticipatory time, motor cognitive skills, and reaction speed, were positively impacted by SVT (Table 2). On the other hand, results based on longer-lasting visual stimuli or stimuli that appeared in the periphery of the visual field were found to be unaffected by SVT (Appelbaum et al 2011).

Safety and adverse events

None of the studies in this analysis addressed reporting safety issues or adverse occurrences as one of their objectives. Participants using strobe glasses did not result in any safety concerns or unfavourable incidents, according to any of the research.

DISCUSSION

The purpose of this structured review was to summarize the impact of SVT on visual and/or motor performance by looking at 13 research that described its use in healthy and fit athletes. Since all of the research studies included in this review have been completed since 2010, SVT is a relatively recent field of study. Nonetheless, the utilization of this approach in diverse training environments has resulted in notable variations both amongst and within treatments. We reviewed the literature to see what studies had been done with athletes; prior research indicates that visual skill training could help athletes perform better.

Protocols

Stroboscopic devices

The two devices included in the research all had distinct manufacturer operating levels, so there was no standard way to record the "*blink rate*" or strobe effect frequency. To provide the stroboscopic effect used in the training program, Senaptec Strobe glasses (Appelbaum et al 2011, Hülsdünker et al 2021, Wilkins et al 2018, Zwierko et al 2024, Vasile et al 2023, Sudesan et al 2023, Hülsdünker et al 2021) were used. Eight distinct frequencies cause these glasses to flicker, from 1 Hz (level 8; considered toughest because it receives the fewest visual samples) to 6 Hz (the easiest because it receives the most visual data). At each frequency, the glasses change from transparent to opaque. Additionally, there are three settings to adjust the stroboscopic effect: both eyes, left eye alone, and right eye only (in one-eye mode, the non-strobic lenses stay opaque). Phase-wise stroboscopic occlusion of perception through frequency modulation and alteration of the dark phase ratio was achieved with the use of shutter glasses, namely the Nike SPARQ Vapor Strobe (Nike, USA). Depending on the (load) level selected, the Nike Vapor Strobe occludes from around 60ms dark phase (level I) to approximately 900ms dark phase (level VIII), with a constant 100ms light phase. As the ratio of dark to light increases from stage I to stage VIII, the frequency of images diminishes.

Strobe settings

Regarding the frequency of strobe settings and the usage of fixed versus variable strobe frequency settings, there was a lack of standardization. Researchers Ellison and his colleagues looked at the effects of SVT given at a set frequency of 4 Hz (Nike Vapor Strobes: level 3, 100ms clear: 150ms opaque), and they discovered that right after just one SVT session, individuals in the intervention group showed noticeably improved anticipation. These results have since been used by other studies to support their choice of strobe rate setting.

Therefore, more research is needed to ascertain whether there is a strobe frequency that is ideal for both visual and motor learning, as well as whether or not participants' exposure to a fixed strobe frequency will result in a bigger (or even less) impact from SVT.

Frequency and duration of interventions

This evaluation shows that there was a great deal of variation in the frequency, length, and quantity of SVT treatments used in the trials. The interventions varied from one SVT session to several sessions spread out over a period of ten weeks. The paucity of detail offered in certain papers about the intervention protocols further complicates interpretation in our analysis.

Post training test points

In every study, post tests were conducted within a day, demonstrating the direct impact of SVT on various outcomes. We know less about the long-term efficacy of SVT in any population since retention-test data, which are perhaps more relevant to the practical application of SVT, were only obtained in 4 of the trials. Future research is necessary to ascertain whether the effects of SVT persist for longer than four to six weeks and whether the frequency and duration of SVT actually influences retention.

Outcomes

Across the studies, the effectiveness of SVT was evaluated using a variety of outcomes, such as tests of motor function and visual skills (such as reaction time, visual memory, and processing speed). These results underline the necessity for future clinical trials to take into account their choice of outcomes in connection to the SVT tasks being offered, and they offer compelling evidence for the positive training effects of employing SVT for task-specific dynamic balancing training, at least in younger individuals. According to the Zweirko research, stroboscopic intervention significantly improved visuomotor and visual performance on three out of five measures, with visuomotor function being enhanced more than sensory processing. The study by Sudesan J showed that acute SVT exposure while wearing eye-hand coordination and visual reaction time significantly enhanced performance. The Appelbaum research demonstrates a noteworthy enhancement, indicating that stroboscopic training may enhance one's capacity to interpret visual information in the centre visual field more rapidly. In the peripheral attention task, neither group showed any differences. The stroboscopic training used here, according to research by Smith and Mitroff, decreased the timing mistakes' magnitude and variability when participants had to estimate when a moving visual stimulus would arrive at a certain spot. The only research that showed the drawbacks of SVT was that done by Antonia Loana Vasile. In her paper, she proposed that the skills of this training method include: intersegmental coordination, focused attention, distributive attention, memory, visualization, choosing an ideal climbing speed, body placement on the wall, sensory reorientation on proprioception, and central and peripheral vision. The athletes listed their increased mental exhaustion, increased vertigo, and impaired ability to discern hold colour as some of the drawbacks of training.

CONCLUSION

This research aims to review the scientific literature that investigates the impact of SVT on athletes' motor and visual performance. Engaging in stroboscopic training can enhance both short-term and long-term memory retention of visual information. Athletes stand to benefit greatly from stroboscopic training as it can notably improve their visual memory, thus potentially boosting their sports performance. Stroboscopic training has been found to enhance motion detection and central attention, although it does not seem to have the same effect on sustained attention. Studies indicate that there are enduring advantages to stroboscopic vision training when it comes to perceptual processes. Stroboscopic training can expedite visuomotor reactions, consequently aiding athletes in their on-field performance. By training with stroboscopic vision, athletes may improve their anticipatory timing skills. Wearing stroboscopic eyewear can result in significant enhancements in both visual and visuomotor functions. Further studies are necessary before SVT is routinely used in sports training.

Future recommendations

- There is no such proper research article regarding strobe usage published in underdeveloped and developing nations.
- Mention the mode of strobe used to maintain a proper protocol for future researchers.
- Include the effects of the strobe being retained after the retention period.
- Mention the experience of adverse effects or not regarding the usage of the strobe to have a safety protocol.
- A proper training intervention protocol should be mentioned according to the age criteria, which will be helpful for future researchers.
- Include the feedback or user experience from the participants regarding the strobe usage before and after the intervention, including both training experience and on-the-field experience.
- Include the test points after every single intervention of strobe to know the consistency improvement in performance.
- Perform studies regarding the effect of SVT on balance in healthy populations.
- Mention the effect and usage of each frequency in strobe settings, which was unclear to date.
- There is no proper protocol regarding the reintervention of strobe in the same healthy individuals and the total period of effect of strobe in the healthy individuals.

AUTHOR CONTRIBUTIONS

Sudesan Jothi: writing – review & editing, writing – original draft, methodology, formal analysis, data curation, conceptualization, investigation. Dr. Jagadeswaran D.: supervision, methodology, Dr. K. Kanmani: review & editing, supervision.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ACKNOWLEDGMENTS

Researchers thankfully acknowledge TAC committee members and Research Department of Saveetha Institute of medical and technical sciences (SIMATS).

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ORIGINAL ARTICLE

Innovation in metaverse virtual reality technology and gamification physical education learning styles on students' motor skills

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ABSTRACT

The study integrates information technology into physical education teaching. It used a mixed-method with a quasi-experimental method. The study was conducted on 30 students at Elementary School Jeruk 1 Surabaya. Since the participants came from three different class groups previously, different teaching methodologies were employed for each group: the teaching style was given to the control group, and in experiment 1, the treatment with physical education teaching style and gamification provided. The experiment 2 group was treated using virtual reality. The results of the research showed that virtual reality and exergames provide a relaxed and enjoyable learning environment. However, the study indicates that a well-structured 6-week virtual reality program can significantly improve motor coordination, coordination, and reaction time results for students of Elementary School Jeruk 1 Surabaya. Data from the 7 m single-legged run test had a T result of ($p < .012$), the 9 m two-way run test showed VR+G results ($p < .001$), the lateral jumps test had a G result ($p < .004$), the left-hand handgrip test had a G result of ($p < .003$), the plate-tapping test had a G result of ($p < .003$), and the flamingo test had a G result of ($p < .01$). Gamification is highly favoured by elementary school students compared to the PTS group.
Keywords: Physical education, Metaverse, Gamification, Motor skills.

Cite this article as:
Utamayasa, I. G. D., Kusuma, A. I., & Ariani, L. P. T. (2025). Innovation in metaverse virtual reality technology and gamification physical education learning styles on students' motor skills. *Journal of Human Sport and Exercise, 20*(2), 574-584. https://doi.org/10.55860/pd3pdm39

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Submitted for publication December 13, 2024.
Accepted for publication January 28, 2024.
Published March 04, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/pd3pdm39

INTRODUCTION

In recent years, the development of education as well as the reforms and openness have become very important in the education system. One of the main issues is that students find it difficult to perform motor tasks during physical education learning. Therefore, urgent problems in physical education include single teaching methods, lack of teaching style capabilities, lack of innovation in learning, and lack of comprehensive technical analysis (Castillo, 2018). This methodology increases motivation and facilitates the teaching and learning process (Muntaner Guasp et al., 2020). Latest methodologies, particularly gamification, have emerged and gained relevance in recent years and have been widely used in the field of education (Klock et al., 2020). In this environment, the most important game elements are to be included in education. Although the use of gamification has been shown to increase students' motivation and physical fitness (Ferriz-Valero et al., 2020), its impact on learning improvements remains unclear (Robson et al., 2015). This is most likely due to the lack of research in the field of education, particularly in sports (Fernandez-Rio et al., 2020). The results of the study (Utamayasa & Mardhika, 2024) showed a significant positive impact of virtual reality technology on students' motor development and confidence in performing movements compared to traditional learning.

Conversely, virtual reality and gamification have become relevant in various fields of education and have been quickly adopted for different purposes. This study introduces the application of metaverse-based virtual reality in teaching activities and then uses this technology to build a sports teaching system. Based on this, one effort to help primary schools not struggle in translating motor tasks during learning is to have an approach that can bridge this gap by implementing metaverse virtual reality and gamification. The study showed that using virtual reality applications boosts primary schools' confidence during learning activities and helps students who have low performance. Therefore, physical education teachers must make changes in terms of techniques, motor skills practice, and traditional teaching models that can no longer be used (Liang et al., 2023).

The number of studies published on the use of this technology for educational purposes continues to increase. Educational institutions are now moving quickly to adopt virtual reality as an educational and training tool because it can be directly applied to the teaching and learning process, resulting in positive learning outcomes across various domains (Kavanagh et al., 2017). This process offers real-time multisensory feedback during task-oriented training, thus facilitating motor learning. This opens up opportunities for the development of a virtual reality and gamification physical education system, injecting new scientific elements into the modernization of physical education. Virtual reality technology can be used in learning and has proven effective in the development of physical education (Martins et al., 2012).

This study introduces for the first time the application of metaverse virtual reality and gamification in teaching styles in these activities and then uses this technology to build a sports teaching system. Next, we analyse the importance of integrating it into teaching models. This study shows that the new teaching model has a good effect on improving teaching quality. This study advances a technology-based physical education teaching model. In the field of physical education, interest and demand for virtual reality-based learning activities are increasing and are currently being developed (Gurrin et al., 2014). Similarly, it is necessary to investigate how children perceive effort, motivation, compliance, and satisfaction when undergoing virtual reality activities during sports lessons in a school environment (Polechoński et al., 2020), considering some differences in the literature reporting significant learning outcomes when comparing virtual reality with other active learning or traditional learning methods (Moro et al., 2020). In addition, previous research on the use of virtual reality in physical education is still lacking compared to other methodologies. Therefore, this study aims to analyse the effect of using virtual reality and gamification in physical education learning styles on students' motor skills and perceived efforts.

Using the designed technology, advantages in physical education will prominently provide an effective learning environment. New technology reforms promote the application of the metaverse in sports teaching. Research shows that a teaching environment that uses this new technology can attract more students to participate in sports activities. The study on the application of metaverse-based virtual reality and gamification in physical education teaching is relatively detailed. The application of this technology helps schools successfully carry out sports activities. It can be concluded that using this technology can enhance students' learning outcomes (Yu & Mi, 2023). Additionally, based on these findings, by presenting a physical education model that integrates metaverse and gamification technology, this study intends to suggest metaverse-based physical education as a new alternative. Therefore, physical education will also be one of the beneficiaries of metaverse technology (Yu & Mi, 2023). Teachers must implement more advanced metaverse technology and concepts to refine and complement current physical education.

The state of the art of this research is viewed from the problem of practical physical education learning styles, where teachers mostly demonstrate tasks and students only practice the tasks given by their teachers. Therefore, the learning style becomes monotonous and students are less active in the learning process. Thus, the learning style can be replaced with a more active, engaging methodology and student-centred options that encourage students' participation and engagement in improving motor skills. Previous research has used augmented reality-based technology in the learning process. Augmented reality is another virtual technology that has been shown to enable students to enhance performance by considering different dimensions, facilitating the understanding of theoretical parts, and accelerating the development of students' motor skills (Moreno-Guerrero et al., 2020). Additionally, the use of digital *book creators* has also been used to enhance students' motor skills (Hasanah, 2021). Other studies also state that the use of video-based visuals has been used in physical education learning to improve students' motor skills (Mödinger et al., 2022).

The novelty of this study lies in demonstrating the capacity of virtual reality and gamification on physical education learning styles to enhance children's motor competence. The benefits of motor skills in physical education learning help physical activities and can positively impact students' cognitive, social, and emotional development. Based on this reality, one effort to help primary schools not struggle with motor tasks during learning is to have an approach that can bridge this gap by implementing metaverse virtual reality and gamification in physical education learning styles.

MATERIAL AND METHODS

This study integrates information technology into physical education teaching. The study design uses a *mixed-method* with a quasi-experimental method. Qualitative data were collected after virtual reality and gamification interventions to find mechanisms that potentially explain quantitative results (Fetters et al., 2013). This study was conducted on students at Sekolah Dasar N Jeruk 1 Surabaya, totalling 30 students. Therefore, considering that the participants came from three different class groups previously, different teaching methodologies were allocated for each group: a teaching style was given to the control group, and experiment 1 was given physical education and gamification teaching styles. Experiment 2 was treated using virtual reality. For qualitative data, to meet the research objectives, motor skills and perceived effort were qualitatively explored through two steps: first, semi-structured individual interviews and group discussions.

The procedures in this study are:

1. In the initial stages, participants were evaluated before and after the intervention, consisting of two weekly sports sessions each lasting 50 minutes for six weeks.
2. To evaluate motor skills, the *sportcomp* motoric test was described and validated by Ruiz-Perez (Morillo-Baro et al., 2015). It consists of 5 motor skills tests including: 7 m run with both feet together, 7 m run with one foot, lateral jump, 9 m two-way run, and transfer with support. Each participant performed three trials on each side, and the highest average score was taken as the result. The next test recommendation is the balance test (Rami & Prabhakar, 2018). Participants followed the research procedure by signing a consent form. All procedures comply with the research ethics code.
3. The three groups followed the research procedure. Gamification was developed and designed during the intervention with the underlying context of the film Avatar 2. Researchers provided an introductory video to students before the intervention connecting various activities with this theme. In the gamification group, students were divided into four groups. Explanations about the scores they could achieve in each activity were given, and at the end of each session, each group could exchange these points for game cards that could be used in the next session.
4. The virtual reality group had special treatments equipped with glasses and Kinect Sports Xbox. VR technology training (20 minutes/session; 2 sessions per week; total 6 weeks; total 240 minutes/participant. The commercial VR training video game used was Just Dance 2022. Data collection before and after the intervention was carried out by researchers, under the supervision and support of the teacher.

Data are presented as ± standard deviation, sampling estimation was carried out using G*Power 3.1.9.7 software. Statistical analysis was performed using Jamovi software for Windows, version 2.3.12. Repeated measures ANOVA tests were conducted to analyse the effect of the teaching methodology on related variables. The expected results of this study are that using virtual reality and gamification applications make students confident during the learning activities and help students with low performance. This study aims to analyse the effect of using virtual reality and gamification in physical education learning styles on students' motor skills and perceived effort.

The document mentions that the study involved 30 students (15 female and 15 males; aged 7–12 years) from Sekolah Dasar Negeri 1 Jeruk Surabaya. Using this information, I can format the demographic data into Table 1.

Table 1. Characteristics of the participants.

Characteristic	Number (n)	Percentage (%)
Total participants	30	100
Gender		
- Male	15	50
- Female	15	50
Age group		
- 7–9 years	10	33.3
- 10–12 years	20	66.6

The data collection technique in this mixed-method study uses the *concurrent embedded* model, where quantitative and qualitative data collection is carried out simultaneously, and alternately within a short time interval. Quantitative data collection techniques are the main focus of the research by providing instruments that have been tested for validity and reliability to the entire sample. Qualitative data collection techniques are carried out with in-depth interviews, documentation, and extensive use of observations and data collection using a natural setting. Data analysis uses descriptive statistics.

RESULTS

The study involved 30 students at Sekolah Dasar Negeri 1 Jeruk Surabaya, Indonesia. A total of 30 students (15 female and 15 males; average age 7-12 years). The results are reported in the following order: (a) quantitative and intervention results, (b) qualitative results, and (c) mixed methods (integration).

Quantitative findings

Table 2. Findings from the study. Results are presented as mean ± SD.

		Pre-Intervention			Post-Intervention			*p*
7 m feet-together run test	VR+G	3.12	±	0.43	3.33	±	0.45	3.23
	G	3.67	±	0.56	3.78	±	0.54	0.023
	T	3.20	±	0.67	4.05	±	0.66	0.023
7 m single-legged run test	VR+G	3.02	±	0.45	3.87	±	0.43	0.56
	G	2.70	±	0.44	3.43	±	0.54	0.243
	T	3.01	±	0.66	3.02	±	0.67	0.012**
9 m two-way run test	VR+G	12.02	±	1.23	11.98	±	1.23**	0.001**
	G	12.05	±	1.78	12.04	±	1.34	0.232
	T	12.03	±	1.56	16.8	±	1.09	0.233
Displacement with support test	VR+G	16.7	±	3.37	18.6	±	2.67	2.12
	G	17.9	±	4.56	19.2	±	4.63	0.125
	T	15.6	±	3.87	37.6	±	4.67	0.022
Lateral jumps test	VR+G	30.8	±	6.78	35.5	±	5.09**	45.34
	G	31.6	±	6.56	36.6	±	6.85**	0.004**
	T	32.2	±	8.23	33.6	±	5.94**	0.235
Left-hand handgrip test	VR+G	7.23	±	4.67	23.8	±	6.55**	237.8
	G	7.78	±	5.54	30.6	±	7.66**	0.003**
	T	8.34	±	8.23	34.5	±	9.12	0.764
Plate-tapping test	VR+G	5.07	±	0.65	9.87	±	6.23**	297.6
	G	5.78	±	0.54	10.2	±	8.13	0.003**
	T	6.43	±	0.76	10.7	±	8.56	0.657
Flamingo test	VR+G	11.9	±	1.65	3.56	±	1.43	11.45
	G	11.7	±	2.13	5.66	±	2.21	0.001**
	T	11.4	±	1.54	4.37	±	2.45	0.125

*Note. VR: virtual reality; G: gamification; T: traditional. * Different from pre (p < .05); ** Different from pre (p < .001).*

In the table above, the 7 m single-legged run test has a T result of ($p < .012$), the 9 m two-way run test shows VR+G ($p < .001$), the lateral jumps test has a G result of ($p < .004$), the left-hand handgrip test has a G result of ($p < .003$), the plate-tapping test has a G result of ($p < .003$), and the flamingo test has a G result of ($p < .01$).

Qualitative findings

There are two main indicator categories identified: (a) perceived effort and (b) improvement in motor skills. These results are supported by narratives obtained from participants. In the specific case of VR activities, no participants stated that activities in the VR field resulted in improvements in their motor skills.

Mixed method findings

Table 3. Combined quantitative and qualitative results.

Measurement results	Quantitative	Qualitative
PCERT (children's effort ranking table): effort levels between 1 (very, very easy) and 10 (so difficult that you would stop) with an average value of 5 (starting to get difficult)	Students rated perceived effort higher in PTS compared to the other two learning groups (p < .012)	Effort was experienced when performing activities that required continuity. On the other hand, these activities demanded greater mental effort, such as juggling with a ball or those requiring motor control and coordination. Lastly, VR activities did not require much effort from the students.
Motor tests: determine motor coordination in students aged 7-10 years through 5 tests (7 m run, 7 m single-legged run, lateral jump, 9 m two-way run, and transfer with support). Handgrip test, flamingo test. Eurofit: Measures grip strength and balance.	All three groups had interventions in the 7 m single-legged run test T (p < .012) and lateral jumps test (p < .004). Only two GAM groups showed improvement in the left-hand handgrip test (p < .003). Only the PTS learning group scored lower in the transfer movement with the flamingo test (p < .001). The 9 m two-way run test had VR+G (p < .001).	These activities had limited time to show motor improvements. VR activities did not require physical effort and had little impact on improving physical performance in non-virtual environments. What could be improved through VR are activities related to hand-eye coordination and reaction speed.

DISCUSSION

The use of technology that enables the creation of interactive environments and the provision of a form of physical enhancement through the use of exergames via VR. Our study results are similar to other literature studies showing that virtual reality can improve coordination (Barbosa et al., 2020). Statistical analysis indicates that gamification can improve students' motor skills in the lateral jump test. The study results (Zhao et al., 2024) show that exergames can enhance student sports learning and the impact of exergames on student sports learning outcomes. Virtual reality and exergames can provide a relaxed and enjoyable learning environment. The integration of exergames and virtual reality into the physical education teaching style aligns well with student preferences. As a result, students transform from passive and receptive learning habits into spontaneous and active learning, ultimately achieving high-quality physical education learning. In conclusion, exergames align with modern educational concepts aimed at developing students and improving their health quality and social adaptability (Zhao et al., 2024).

From the document provided, the p-values for male and female comparisons in Table 2, Table 3, and Table 4 are not explicitly mentioned as gender-specific comparisons. For the interventions and tests listed, significant differences are reported when the p-value is less than .05. These differences are attributed to group-specific interventions rather than gender comparisons. If you need specific gender-based analysis, the document does not provide separate male vs. female statistical results. Clarification from the study authors or additional statistical analysis might be required to address gender-specific differences. Let me know if you'd like assistance with further analysis or clarifications.

However, this study shows that a well-structured six-week virtual reality program can significantly improve motor coordination, coordination, and reaction time in students at Sekolah Dasar Negeri 1 Jeruk Surabaya. Besides the small number of participants and the relatively short intervention time, this research has other limitations, such as the lack of medium- and long-term verification of subjects' participation in different physical activities. Future studies should focus on these issues. Future technology, especially in physical education, will undoubtedly bring advancements and optimize the combination of virtual reality and exergames experiences. The results show that VR and exergames can significantly improve children's motor skills compared to the control group, consistent with previous studies (Jelsma et al., 2013), which conducted VR training (Nintendo Wii Fit) for 25 minutes, 4 times a week for 3 weeks and found that children's motor function significantly improved.

Meta-analysis results show that gamification and teaching styles using VR positively influence students' motor skills in sports learning (sig < .012), indicating that gamification applications can facilitate student sports learning with statistical significance. The reasons may include the following aspects:

1. Gamification is characterized by fun, flexibility, and competence. Implementing learning styles through gamification can increase participation and learning interest, thereby motivating them to learn actively. Additionally, students gain a sense of accomplishment in completing gamification tasks, further enhancing their confidence in learning (Hu et al., 2022).
2. Gamification using VR can provide a relaxed and enjoyable learning style environment. Students can repeatedly simulate exercises in this environment, creating a stronger sense of participation and actual experience, fully enjoying the fun and charm of sports. Moreover, the learning environment created through games allows students to form a common perception of learning movement techniques.
3. Integrating exergames into sports programs aligns well with student preferences. As a result, students transform from passive, receptive learning habits to spontaneous, active learning, ultimately achieving high learning quality. In conclusion, exergames align with modern educational concepts aimed at developing students and improving health quality and social adaptability (He & Hao, 2014).

VR gamification provides a platform for students to express themselves fully. Through game media, students can confidently display themselves, encouraging strong intrinsic motivation to engage more actively in sports classes. Success rewards in games inspire students to feel pride and satisfaction, gradually boosting their confidence and self-identity, leading to a positive learning attitude, increased exercise frequency, and continuous skill improvement throughout the course. Therefore, gamification strategies should be implemented in student-centred teaching models to promote active learning, collaboration, and problem-solving in constructivist models (Ferraz et al., 2024). Gamification can be presented as a means to induce positive changes in student behaviour by increasing physical activity levels and emotional states, supporting positive attitudes and motivation towards physical activity practices (Goodyear et al., 2021). There is growing interest in gamification among teachers and educational institutions (Figueroa Flores, 2016). Using games in this context has proven to have a significant impact according to research conducted by (Liu & Lipowski, 2021). Therefore, it is crucial to analyse the educational context and design appropriate gamification tailored to specific students. A novel aspect of this review is that virtual reality is highly suitable for incorporating motor learning principles.

Exergames and VR positively impact elementary school students by providing positive emotional experiences and enjoyment, thus enhancing their intrinsic motivation for physical activity (Hou & Li, 2022) (Bae, 2023). Additionally, it has been observed that VR involves specific motor and cognitive skills and the ability to optimize desired movement trajectories (Dong et al., 2023), highlighting its interest in developing and enhancing motor skills. Participants in this study may not have perceived such improvements due to the short intervention duration or the insensitivity of the measurement outcomes used.

This is evidenced by the improvement in the lateral jump test in both GAM study groups compared to the PTS study group ($p < .004$). Additionally, the PTS study group, along with the PTS group, showed a decline in post-intervention support transfer test performance ($p < .235$), possibly due to the speculative lack of motivation in this group compared to the GAM group and not due to deteriorating motor skills. Although the impact of GAM on sports motivation is beyond this study's scope, motivation can also be considered a potential determinant of participants' perceived effort, which was interestingly rated lower by both GAM study groups. Based on qualitative results, some participants did not perceive VR activities as demanding, indicating a disruptive effect of VR on the PTS+GAM+VR group. Additionally, significantly lower perceived effort in both GAM groups (combined with or without VR) coincides with participants' relative perception of effort regarding activity type and participation format (Criollo-C et al., 2024). VR and Gamification can enhance education quality and active student participation. This study presents several noteworthy strengths. Firstly, this research is easily applicable and implementable in the educational context of elementary school children.

CONCLUSIONS

Gamification is highly favoured by elementary school children compared to the PTS group. When combined with VR, it can enhance elementary school children's motor skills. As educational and societal needs and demands change, traditional learning needs to be reinforced and transformed through new technology applications and approaches to adapt and meet new needs. The use of gamification and virtual reality in physical education is becoming more popular as a means to satisfy students' desire for more interactive, immersive, engaging, and meaningful learning. Based on the results, gamification can positively influence educational activities and enrich virtual reality experiences to create a more interactive, engaging, and motivating learning environment. Most studies report positive results regarding improving motor skills and student satisfaction. Both students and teachers positively assess its usefulness in education, highly appreciating its role in transforming traditional teaching and learning activities and highly valuing the benefits it can bring to the educational process by facilitating and supporting teachers and successfully meeting students' needs and demands for more effective learning benefits.

AUTHOR CONTRIBUTIONS

Design of the Study, IGDU and AIK; Data Gathering, LPTU; Statistical Evaluation, IGDU; Data interpreting, AIK; Writing of the Manuscript, IGDU and AIK; Search of the Literature, AIK and LPTU. Each author has reviewed the final draft of the manuscript and given their approval.

SUPPORTING AGENCIES

The authors would like to thank all parties who helped complete this study, especially the Ministry of Education, Culture, and Technology of the Republic of Indonesia for the 2024 fiscal year funding contract number: 109/E5/PG.02.00.PL/2024,034/SP2H/PT/LL7/2024,070.10/kontrak/LPPM/VI/2024. Through this scientific research, this study was well conducted and ran smoothly.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ETHICS STATEMENT

This research followed ethical standards and received approval from the Institutional Ethical Committee Universitas PGRI Adi Buana Surabaya numbered 165.7 / ST / LPPM / XI / 2024 dated 15 November 2024.

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ORIGINAL ARTICLE

Functional movement test performance improves in youth ice speed skaters after 8-week FMS training

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ABSTRACT

In sports competitions worldwide, the scheduling of tournaments is tightly packed, imposing strict demands on athletes' physical fitness. In high-intensity environments, the risk of sports-related injuries significantly escalates. The Functional Movement Screen (FMS) test has gained recognition among coaches in multiple countries and has been employed within sports teams. To more effectively and rapidly identify issues among athletes and devise corresponding intervention training plans, this study combined interview methods to understand the training situation of a speed skating team. It conducted FMS screenings on 16-speed skaters, exploring their overall body control stability, joint flexibility, and potential issues in overall proprioception. Specific intervention plans were developed based on identified problems. Results: Before intervention training, the average score of FMS tests for speed skaters was (15.38 ± 0.92) points, which increased to (19.13 ± 0.64) points after training. Conclusion: Through the intervention training devised in this study, athletes exhibited significant improvements in various scores and overall FMS scores, thereby enhancing their athletic performance.
Keywords: Physical education, Motor skill, Physical training, Athletes performance, Adolescent.

Cite this article as:
Qu, Q., Hurr, C., Qiu, X., Zhang, J., & Kim, S. (2025). Functional movement test performance improves in youth ice speed skaters after 8-week FMS training. *Journal of Human Sport and Exercise, 20*(2), 585-595. https://doi.org/10.55860/rvwbta64

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Submitted for publication November 11, 2024.
Accepted for publication December 20, 2024.
Published March 26, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/rvwbta64

INTRODUCTION

In today's speed skating competitions, athletes need to continually improve their overall physical fitness to effectively showcase their techniques and tactics. Only by enhancing these qualities can they adapt to the constant innovation and evolution of skills and strategies in competitions. Against this backdrop, elevating the quality of training becomes imperative. However, training with incorrect movement patterns can lead to sports-related injuries during practice or competitions, significantly increasing the risk of athletes getting injured (Ruotong, Jiahe, & Shibo, 2022). Numerous scholars have found that implementing well-designed and targeted physical conditioning training programs can significantly reduce the likelihood of sports injuries. Therefore, it's evident that physical conditioning training holds immense importance in the daily training regimen of athletes (Boyle, 2016; Chorba, Chorba, Bouillon, Overmyer, & Landis, 2010; Lily, 2011; Santana, 2015; Xiaolin & Chitian, 2015).

In speed skating, whether coaches or researchers serving the team, the primary attitude towards athlete injuries is generally prevention, followed by treatment. To reduce the occurrence of sports injuries, early prevention is essential (Rahimi, Samadi, Abbasi, & Rahnama, 2023). Scientific and reasonable physical fitness training is one of the important means to reduce the occurrence of sports injuries. When athletes engage in physical fitness training, the first thing to consider is their basic movement abilities (Zarei, Soltanirad, Kazemi, Hoogenboom, & Hosseinzadeh, 2022). FMS (Functional Movement Screen) uses simple means to collect information and data on three aspects of subjects: basic movements, neuromuscular control of movement patterns, and the subjects' foundational movement abilities (Xiaolin & Chitian, 2015). Combining results and data helps identify and pinpoint serious deficiencies in subjects' movements, determining where their movement abilities are restricted or asymmetrical. In other words, FMS is an organized evaluation system for normal movement patterns. In 2003, Gray Cook further introduced the concept of the "*Movement Competency Pyramid*." Through FMS screenings, assessments can swiftly, conveniently, and accurately identify weaknesses, asymmetries, and restricted movements within an individual's body (Cook, 2010). Subsequent training can then be tailored based on these test results, employing more scientific and targeted methods to address and improve the obstacles and deficiencies found in the subject.

This study, in conjunction with the specialized characteristics of speed skating, utilized FMS screening to identify functional issues among 16-speed skaters. Based on the FMS results, corresponding intervention training was devised, laying theoretical and practical foundations to enhance athletes' performance, reduce speed skating injuries, and provide a basis for intervention training. We hypothesize that training plans devised through FMS testing can improve athletes' FMS test scores while enhancing their performance.

METHODOLOGY

Participants

This study focuses on the application of the Functional Movement Screen (FMS) in speed skating physical training. Sixteen athletes from the speed skating team were selected as participants, all of whom are active members of the team and possess a skating level at or above level one. Written informed consent was obtained from each participant before the experiment. Before participating in the study, all participants completed a brief questionnaire regarding personal information such as height, weight, and any disabilities.

Table 1. Basic information for athletes (n = 16).

Age (years)	Weight (kg)	Height (cm)	Training years (years)	Level
15.13 ± 1.46	60.70 ± 4.31	168.4 ± 5.57	6.50 ± 1.07	China National Level

Experimental design
As needed, FMS testing was conducted on 16-speed skaters, encompassing seven components: deep squat, hurdle step, in-line lunge, shoulder mobility, active straight-leg raise, trunk stability push-up, and rotary stability tests. The test outcomes serve as essential data sources for this study.

The FMS testing took place at the Jilin Institute of Physical Education training centre. The first test, before intervention training, occurred on July 30, 2022, while the second test, following the completion of intervention training, took place on September 31, 2022.

(1) Identifying research subjects, selecting them based on preliminary tests, and collecting basic information such as name, gender, age, athletic level, and other indicators.
(2) Athletes must perform movements according to the experimenter's instructions during FMS testing. Each test is conducted three times, and the scores are recorded.
(3) During the Functional Movement Screen (FMS), record the individual scores for each test item. If bilateral movements are tested, record the scores for each side.
(4) Perform phased data processing and analysis on the acquired data.
(5) Through data analysis, discuss and analyse various evaluation indicators. Based on the athletes' scoring results, propose reasonably scientific intervention training methods to effectively reduce the risk of athlete injuries and improve their athletic performance.

FMS Test
As required, FMS testing was conducted on 16 athletes, comprising seven components: deep squat, hurdle step, inline lunge, shoulder mobility, active straight-leg raise, trunk stability push-up, and rotary stability tests. The test outcomes serve as essential data sources for this study.

Measurement equipment includes a ruler, Functional Movement Screen Test Kit, FMS test evaluation form, mini bands, Swiss balls, dumbbells, barbells, yoga mats, foam rollers, massage sticks, balance pads, and others.

Intervention
(1) Experimental Period: August 2022 to September 2022, lasting for 2 months, equivalent to 8 weeks.
(2) Experimental Arrangement: Conducting intervention training three times a week, carried out after regular training sessions, and ensuring it does not disrupt the coaches' training plans. Each training session lasts between 45 to 50 minutes.
(3) Design of intervention Training: Aimed at enhancing athletes' performance based on the FMS test scores of active speed skating athletes, the intervention training was designed considering both the test outcomes and the characteristics of speed skating. The FMS intervention training includes: ① Flexibility training, focusing on joint mobility and muscle flexibility; ② Stability training, emphasizing the sequence of basic movement patterns to demonstrate excellent posture control ability; ③ Movement pattern reconstruction, integrating fundamental flexibility and stability into specific movement patterns to enhance overall body coordination.

Unlike traditional physical training, when devising intervention training plans (Carlos, 2019), numerous factors are considered in addition to the scores of each test action. The sequence should follow from basic flexibility → basic stability → construction of movement patterns, and adhere to the following principles:

(1) When scores are equal, symmetry consistency is prioritized. FMS test actions are designed based on fundamental human movements, thus having a certain sequence.
(2) Principle of Action Hierarchy: Some athletes may exhibit multiple incorrect movement patterns, where some issues arise from poor flexibility while others stem from inadequate stability. In such cases, addressing the athlete's flexibility issues should take precedence before correcting their stability.
(3) Principle of Progression from Difficult to Easy: Training should gradually increase the difficulty of movement patterns only under conditions the individual can control. For instance, reducing the athlete's base of support, changing or combining exercise equipment, or altering the posture during movements.

Based on the athletes' screening results, an intervention training spanning 8 weeks (3 sessions per week, totalling 24 sessions) has been established. To better intervene in the athletes' training, this program will be divided into three phases. Phase One: Weeks 1-3, focuses on rectifying improper body and movement postures, improving athletes' kinaesthetic awareness, and enhancing muscle coordination and flexibility. Phase Two: Weeks 4-6, aims to improve core stability while intensifying flexibility training. The final phase spans Weeks 7-8, emphasizing reconstruction of athletes' movement patterns. A second FMS test will be conducted after the 8-week training program concludes.

Through investigation and understanding of the athletes, combined with the principles of intervention training formulation, this intervention training plan will focus on several aspects: flexibility, including shoulder joint flexibility and flexibility in the primary injury-prone joints; stability, involving stability of muscles around the primary injury-prone joints and core control ability; athletes' balance; functional strength training for various joints; and finally, reconstruction of athletes' movement patterns. The selection of training plans will primarily reference three books: "*Body Function Training Manual*,"(Xiong & Zhaoche, 2014) "*Body Movement Function Diagnosis*,"(Jun, 2015) and "*Training and Movement - Functional Movement Training System*."(Cook;, Zhang Yingbo, Liang Lin, & Hongbo (Translated), 2011) Addressing these aspects will lead to the proposal of targeted and rational intervention training programs for the athletes.

The formulation of this intervention training program is primarily based on the common issues observed among the athletes. However, in the specific implementation process, the selection and arrangement will be based on the specific physical conditions of each athlete (Savinykh, Stoliarova, Stovba, Khomenko, & Kurchenkov, 2022).

First Stage Training - Flexibility-focused Training

In the first stage of training, our primary focus was on enhancing the athletes' flexibility. This phase involved exercises to improve muscle coordination, kinaesthetic awareness, stretching, and relaxation training. It aimed to rectify issues in athletes' flexibility and establish a strong foundation for the subsequent second-stage training. During the intervention training period of 1 to 3 weeks, our main emphasis was on rectifying improper body and movement postures among the athletes, enhancing their kinaesthetic awareness, and improving muscle coordination and flexibility. Through this phase of training, we observed a significant improvement in athletes' performance regarding movement postures. There was also an enhancement in muscle coordination and kinaesthetic awareness.

Second Stage Training - Stability-focused Training

This stage of training primarily emphasizes the stability of the athletes. Building upon the improvement in athletes' flexibility and muscle coordination, this phase incorporates instability factors into exercises, targeting stability in athletes' spines, cores, various joints, and smaller muscle groups. Compared to the first stage of training, the difficulty level in the second stage has increased. It introduces instability factors atop the foundational exercises. For instance, progressing from a basic hip bridge to a hip bridge with a military march movement, incorporating balance training devices into squat exercises, etc.

Third Stage Training - Movement Pattern Reconstruction
The final stage of training spans 2 weeks, primarily focusing on reconstructing the athletes' movement patterns and providing targeted training for the tested actions.

Figure 1. Shoulder flexibility exclusion test.

To rule out functional issues among athletes, an exclusion test was concurrently conducted during the assessment. This was to see whether the test movements would induce pain, further examining potential risks not covered by the test movements. If pain occurred during the test, it was marked as a positive result "+". If the exclusion test showed a positive result "+", the corresponding test movement's score was recorded as 0, without scoring the exclusion test itself. Through the assessments, none of the athletes showed any signs of pain.

Statistical analyses
FMS testing was scored using a scale, obtaining scores for athletes before and after intervention training. The collected data underwent differential analysis using SPSS 20.0, with results presented as mean ± standard deviation (Mean ± SD). Paired-sample t-tests were employed to see changes in FMS test scores before and after intervention training, with a significance level set at .05.

RESULTS

After conducting FMS tests on 16 athletes and organizing the results, for bilateral scoring items, the lower score was recorded. Finally, the scores of the seven individual items were summed to obtain the total FMS test score for each athlete, as shown in the Table 2.

Table 2. Correlation test of test results for male and female athletes.

Test	**Male**	**Female**	***p*-Value**
Deep squat	2.10 ± 0.316	2.20 ± 0.568	1.00
Hurdle step	2.10 ± 0.568	1.90 ± 0.316	.343
Inline lunge	2.20 ± 0.422	2.10 ± 0.568	.660
Shoulder mobility	2.20 ± 0.422	2.40 ± 0.516	.355
Active straight-leg raise	2.70 ± 0.316	2.90 ± 0.483	.288
Trunk stability push-up	2.30 ± 0.422	2.10 ± 0.422	1.000
Rotary stability	1.80 ± 0.316	1.60 ± 0.422	.556
Total screen score	15.60 ± 0.843	15.40 ± 1.350	1.000

From Table 2, it's evident that based on the FMS test scores, male athletes scored higher than female athletes. However, upon statistical analysis, there wasn't a significant difference ($p > .05$) between the scores of male and female athletes, indicating that gender will not have an impact on the subsequent training results.

Table 3. Athletes' test scores for each screening movement (persons).

Score	**Test**						
	Deep Squat	Hurdle Step	Inline Lunge	Shoulder Mobility	Active Straight-Leg Raise	Trunk Stability Push-Up	Rotary Stability
3	3	2	4	6	14	3	0
2	12	11	11	10	2	13	14
1	1	2	1	0	0	0	2

In the overall scoring of athletes, scores mainly concentrated around 2 points, with no athletes scoring 1 point in the Shoulder Mobility, Active Straight-Leg Raise, and Trunk Stability Push-Up tests. However, 14 athletes did not score 3 points in the Rotary Stability test.

Table 4. Comparison of athletes' FMS test scores before and after training.

Test	**Before intervention training**	**After intervention training**
Deep squat	2.25 ± 0.46	2.75 ± 0.46*
Hurdle step	1.88 ± 0.35	2.50 ± 0.54*
Inline lunge	2.00 ± 0.00	2.75 ± 0.46**
Shoulder mobility	2.25 ± 0.46	2.88 ± 0.35**
Active straight-leg raise	2.75 ± 0.46	3.00 ± 0.00
Trunk stability push-up	2.25 ± 0.46	2.87 ± 0.35 **
Rotary stability	2.00 ± 0.00	2.38 ± 0.52
Total screen score	15.38 ± 0.92	19.13 ± 0.64 **

*Note. *p < .05 significant difference before and after intervention training; **p < .01 highly significant difference before and after intervention training.*

Paired sample t-tests were conducted on before and after training FMS test scores using SPSS. The results indicated significant differences after intervention in the deep squat test ($p = .049$), hurdle step test ($p = .009$), and shoulder mobility test ($p = .049$); whereas highly significant differences were observed in the in-line lunge test ($p < .001$), trunk stability push-up test ($p = .009$), and overall score ($p < .001$) post-intervention. The straight leg raise and rotary stability test yielded non-significant results ($p > .05$), yet there was an improvement in the quality of movement execution by the athletes.

DISCUSSION

Through 8 weeks of targeted intervention training, athletes demonstrated an improvement in FMS test scores. The training enhanced the flexibility of the muscles in the lower leg, strengthened the muscles in the lower back, increased flexibility in the thoracic spine, and enhanced stability in the ankle and hip joints. Consequently, significant improvements were observed in the scores of the deep squat test, hurdle step test, and shoulder flexibility test, particularly notable improvements in the in-line lunge, trunk stability, and overall FMS score, alongside enhanced performance during the testing process. Following the training, male athletes exhibited noticeable improvements in shoulder joint flexibility, reduction in shoulder movement restrictions, and a clear enhancement in athletic performance. Over the 8 weeks of intervention training, athletes experienced fewer instances of injuries during routine training compared to other athletes, indicating that intervention training plays a preventive role in sports injuries.

Speed skating is a sport that involves lower limb exertion; hence, it requires balanced and good flexibility in areas such as the waist, knees, and ankles of the athletes to reduce the occurrence of injuries. Combining the technical characteristics of speed skating, investigations into injuries related to this sport, and surveys of athletes, it is found that the most common injuries among speed skaters occur in the knee and ankle joints (Dubravcic-Simunjak, Pecina, Kuipers, Moran, & Haspl, 2003; Quinn, Lun, McCall, & Overend, 2003). Analysing the characteristics of speed skating, the knee and ankle joints are identified as the main joints involved in completing the movements. Instability in these two joints can directly lead to poor performance, hindering athletes from completing technical actions and affecting competition results. If functional movement patterns are affected, the athlete is likely to experience sports injuries. Muscle capability surpassing joint integrity, force pressing on stability, flexibility issues damaging body posture control, and muscle imbalances leading to premature fatigue and undesirable muscle engagement are potential consequences (Cook, Burton, Hoogenboom, & Voight, 2014b). For instance, when an athlete's joint muscles are excessively tense, restricted movement may occur.

In the FMS test scores, we observed that male athletes perform better in stability than female athletes. However, female athletes scored higher than male athletes in areas like shoulder flexibility, straight leg raise, and similar tests measuring muscle flexibility and joint mobility. On the other hand, male athletes exhibited better performance in tests related to strength and core stability such as squatting, trunk stability, and inline lunge. Females showed slightly lower core strength, hip joint, and lower limb strength compared to males, consistent with injury-related reports among speed skating athletes. Due to some female athletes' lower joint stability, muscle strength, control over the pelvis and core, or lower limb and hip joint flexibility, they struggle to execute complete movements effectively (Clark, Rowe, Adnan, Brown, & Mulcahey, 2022).

We also noticed asymmetry between the left and right sides of athletes; some displayed a phenomenon where both knee joints tend to turn inward and were unsynchronized during squatting. This could be due to poor bilateral balance in the athletes' knee and ankle joints, where weaker muscles on one side lead to compensatory movements on the other (Burton, Eisenmann, Cowburn, Lloyd, & Till, 2021). Apart from weak muscle strength, poor flexibility is also a contributing factor. Restricted flexibility in the upper limbs or torso directly impacts an athlete's final performance, fostering incorrect technical movements and potentially causing sports injuries (Fengwu, 2011).

During testing, the most noticeable aspect was the shoulder flexibility test, where male athletes scored lower than female athletes. This could be due to male athletes deliberately developing muscles like the pectoralis minor, rectus abdominis, and latissimus dorsi, causing these muscles to shorten, thereby limiting shoulder flexibility. The adverse consequences of postural changes include ineffective limitations in the range of motion in the glenohumeral joint and scapula (Harper, Bailey, Jones, & Bradley, 2023). Alternatively, poor flexibility in the thoracic spine may result in insufficient stability in the scapula, leading to decreased shoulder flexibility. Therefore, exclusionary tests were conducted on the shoulders.

Based on the investigation and understanding of the athletes, and in conjunction with intervention training principles, this intervention training plan and its formulation will focus on several aspects: flexibility, including shoulder joint flexibility and joint flexibility in injury-prone areas; stability, encompassing the stability of muscles around the injured joints and core control ability (Cook, Burton, Hoogenboom, & Voight, 2014a); athlete's balance capacity; functional strength training for various joints; and finally, reconstruction of the athletes' movement patterns.

Before implementing intervention training, the squat test scores of athletes were primarily concentrated around 2 points, consistent with the characteristics of speed skating and the research findings of numerous scholars (Dubravcic-Simunjak et al., 2003; Okamura et al., 2014). In the long-term and high-intensity training process of speed skaters, knee injuries or risks of injury have been more or less prevalent. Through discussions with coaches, we learned that 80% of athletes had experienced knee injuries. These injuries were mostly attributed to routine training. Coaches find it challenging to promptly observe athletes' tolerance for training load and intensity during training sessions. Additionally, athletes, in their eagerness to rapidly enhance their performance, tend to push their bodies beyond their capacity to withstand training loads, ultimately resulting in injuries.

The intervention training in the first 1-3 weeks primarily focused on improving and addressing athletes' incorrect body postures, enhancing athletes' proprioception abilities, and increasing athletes' muscle coordination and flexibility. In the initial phase of training, the emphasis was on flexibility training, comprising flexibility exercises, stretching sessions, and relaxation exercises in each training session. After 3 weeks of training, athletes showed significant improvements in their posture, with muscle fibres gradually elongating and relaxing, enhancing their elasticity and extensibility. This reduction in muscle tension during movement increased their flexibility and range of motion, heightened neural adaptability, improved signal transmission, and muscle coordination, thereby enabling more effective muscle coordination and movement, ultimately expanding joint mobility.

Compared to the first phase, the second phase of training has increased in difficulty by incorporating unstable elements onto the foundational exercises. For instance, advancing from a basic hip bridge to a hip bridge with a military step, incorporating balance training devices into squat exercises. Athletes, building on the improvements in fundamental movement patterns from the second phase, further enhanced their body stability by introducing tools like resistance bands, Swiss balls, and similar equipment.

The final stage of FMS functional training is action pattern reconstruction. The preceding phases addressed athlete flexibility and stability, while the last phase focuses on reshaping poor movement patterns or postures to enhance athletes' execution and body control. This phase primarily aims to gradually adjust and refine inefficient movement patterns to align with correct biomechanical principles, minimizing injury risks. Exercises like overhead squats, planks, single-leg hip bridges, while enhancing lower body strength and buttocks, also elevate core and lumbar stability, further improving overall strength, stability, flexibility, and control, reducing asymmetry between the athlete's left and right sides.

Moreover, by performing seven simple test movements, we can swiftly and accurately identify the relatively weaker links in an athlete's kinetic chain (Zarei et al., 2022). Based on these findings, we can develop targeted intervention exercise programs to reduce the risk of sports injuries and enhance athletic performance (Silva, Rodrigues, Clemente, Cancela, & Bezerra, 2019). When implementing these intervention exercise programs, close attention to individual differences and responses of athletes is essential to ensure the effectiveness and safety of the plan. Furthermore, regular assessment and adjustments to these plans are necessary to accommodate the athlete's progress and changes.

Under the guidance of coaches, athletes should actively participate in the implementation of intervention exercise programs to cultivate self-monitoring and self-adjustment abilities. Simultaneously, coaches should provide timely guidance and support based on athletes' performances and feedback. Through this approach, we can effectively enhance athletes' athletic performance, reduce sports injuries, and foster their healthy growth and development. This is crucial for both athletes and coaches, so we should take these matters seriously and continue to pay attention to them.

As the intervention training lasted only 8 weeks and the number of athletes involved in the intervention was relatively small, it is recommended to increase the number of test subjects and add a control group in subsequent experiments to further explore the applicability of FMS screening in speed skating. In the future, combining FMS screening with electromyography tests of various muscle groups and epidemiological investigations will be undertaken to develop a more scientific intervention training program suitable for speed skaters.

CONCLUSION

The intervention training intervention designed for athletes in this study led to a significant improvement in the scores of various test items and the total score of the FMS screening, consequently enhancing the athletes' performance. Conducting regular FMS tests allows for an effective, objective, and comprehensive assessment of athletes' functional issues, providing insights into their physical condition for timely intervention training to enhance performance and prevent injuries.

During physical training, it's advisable to integrate the principles of functional and intervention training, arranging sessions sensibly to assist athletes in optimizing their movement patterns for improved performance. There are various methods for intervention training; coaches should align FMS scores with athletes' actual conditions, physiological traits, and sport-specific characteristics when selecting intervention training programs. Adherence to intervention training principles and timely adjustments in training content are essential.

AUTHOR CONTRIBUTIONS

Conceptualization, QQ, CH & SK; methodology, QQ, CH & SK; software, QQ & JZ; validation, CH & XQ; formal analysis, QQ & JZ; investigation, QQ, CH & JZ; resources, QQ & JZ; data curation, CH & XQ; writing—original draft preparation, QQ & CH; writing—review and editing, JZ & SK; visualization, XQ; supervision, SK; project administration, XQ. All authors have read and agreed to the published version of the manuscript. Qingling Qu and Chansol Hurr contributed equally to this work and designated as co-first authors.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Exercise selection for health to elderly after the COVID-19 outbreak

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ABSTRACT

Introduction: Exercise is an important activity for maintaining the health of the elderly after the COVID-19 outbreak. Objective: The research aimed to study was to determine reasons to exercise selection for health to elderly after the COVID-19 outbreak. Methods: Participants were 30 elderly individuals aged between 60 and 80 years, comprising 20 women and 10 men. All participants engaged in regular exercise at a public park within Buriram Municipality for at least three days per week. All participants signed informed consent forms prior to data collection. Data was collected through interviews, observations, and critical incident technique. Inductive analysis was employed, including data triangulation to ensure consistency and reliability. Results: The research findings identified two main themes related to the reasons why elderly individuals choose physical activities: the first theme pertains to the physical health benefits of exercise for the elderly, and the second theme focuses on the mental health benefits of exercise for this population. Conclusions: Elderly selected physical activities based on their unique physical conditions and health issues. Therefore, those involved in selecting appropriate exercise programs for the elderly post-COVID-19 can significantly contribute to both their physical and mental well-being. This is essential to ensure that seniors engage in activities that are tailored to their specific needs.
Keywords: Physical education, Exercise selection, Elderly, Health, COVID-19.

Cite this article as:
Nontakhod, K., Ratchakit, K., Krobtong, P., Ketthaisog, S., Sremsiri, C., & Intanoo, K. (2025). Exercise selection for health to elderly after the COVID-19 outbreak. *Journal of Human Sport and Exercise, 20*(2), 596-605. https://doi.org/10.55860/27ncq749

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Submitted for publication February 12, 2025.
Accepted for publication March 20, 2025.
Published March 26, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/27ncq749

INTRODUCTION

According to the United Nations (UN), populating the aging is an irreversible global trend: people are living longer and having smaller families. It has been projected 1 out of 6 people will be 65 year old or above globally in 2025 (Jee, 2024). It is well-know that the physiological functions of multiple organs progressively decline with age (Guo et al., 2022). Aging is significantly associated with a decline in the musculoskeletal system, impacting individuals' ability to perform daily activities (Frontera, 2017; Kim et al., 2021), both physical and mental health issues can significantly deteriorate the quality of life in the elderly (Murman, 2015; Shen et al., 2021). Consequently, lifestyle modifications such as dietary changes and increased physical activity are crucial for delaying the onset and progression of those conditions in elderly (Jinakote et al., 2024; Mattioli et al., 2022).

To date, exercise training is one of the powerful strategies to delay or prevent the progression of age-related diseases (Ciolac, 2013; Gronek et al., 2021). This is why medical researchers worldwide recommend regular exercise to maintain good health during the COVID-19 pandemic (Chen et al., 2020; Nontakhod et al., 2024). Similarly, during the COVID-19 outbreak, 19 exercise of varying intensity should be performance daily for at least 60 minutes (Cheung, 2019; Min et al., 2019). While hygiene and vaccines play a crucial role in preventing this virus, it’s also widely recognized that building a robust immune defence system through regular exercise is of great importance (Walsh, 2018).

Regular physical activities has been implemented as one the strategies at the international level and has been shown to help prevent and treat noncommunicable diseases (NCDs), improve mental health, quality of life (Font-Jutgla, et al., 2020; Gallegos et al., 2019; Sanchez-Roa et al., 2024). Exercise has demonstrated improvements in both physical and mental health through psychological and physiological mechanisms (Ballmann, 2021; Terry et al., 2020). Helps improving body composition, muscle strength, and cardiorespiratory fitness, while its effects on muscle endurance, flexibility, and body composition (Bai et al., 2021; Gopal, 2014; Iqbal et al., 2024). It also positive effects on emotions and mood, leading to lower levels of stress, anxiety, and depression, and improving positive energy and vitality (Wang et al., 2022). Therefore, the elderly should choose forms of exercise that are suitable for them and gradually increase the intensity (Khoo et al., 2014; Supaporn, 2018), using FITT principle that stands for frequency, intensity, time and type of exercise (Reed and Pipe, 2014).

Previous research has not yet explored the approaches to selecting exercises for post-COVID-19 health, nor the other factors influencing exercise selection. Therefore, researchers are interested in conducting this study to benefit the elderly by helping them select appropriate exercise activities for maintaining their health. The findings of this study will be valuable to those providing care for the elderly post-outbreak.

MATERIAL AND METHODS

Participants

The participants were 30 elderly volunteers aged between 60 and 80 years. Among them, 20 were female (coded as "*Female Volunteers*" or "*FV*") and 10 were male (coded as "*Male Volunteers*" or "*MV*"). Participants were purposively selected from a public park in Buriram Municipality, with the inclusion criterion being regular exercise at the park for at least three days a week. All participants voluntarily agreed to participate in the study and signed informed consent forms. This qualitative research employed the following data collection methods:

1. Semi-structured interviews: Participants were interviewed using a semi-structured interview guide to gather in-depth information about their experiences and perspectives regarding physical exercise.
2. Non-participant observation: The researcher observed the participants' exercise behaviours at the park without actively engaging in the activities. Observations focused on the specific types of exercises chosen by each individual.
3. Critical incident technique: Participants were asked to describe specific instances or events that significantly influenced their decision to engage in physical exercise post-COVID-19. These narratives were audio-recorded, similar to the interviews.

Criteria for selecting research participants included participants were recruited among elderly individuals (aged 60-80 years) of both genders who regularly exercised at a public park in Buriram Municipality for a minimum of 3 and a maximum of 7 days per week. All participants provided written informed consent to participate in the study.

Study organization

The researchers collected data from participants of 30 elderly volunteers aged 60-80 years. The sample consisted of 20 females and 10 males. Participants were purposively selected from a public park in Buriram Municipality, with the inclusion criterion being regular exercise at the park for a minimum of three days per week. All participants provided informed consent prior to participating in the study.

Statistical analysis

This study employed constant comparison analysis to analyses the data. This involved categorizing data, identifying themes, subthemes, and interpreting the data. To ensure the reliability of the findings, triangulation was used to cross-check the consistency of data obtained from three data collection methods: semi-structured interviews, non-participant observation, and critical incident technique.

RESULTS

Elderly individuals select different types of exercise based on their individual physical conditions and health issues. Consequently, those involved in selecting appropriate exercises for the elderly, especially in the context of the COVID-19 outbreak, should prioritize both physical and mental health benefits. This ensures that the elderly can choose exercises that are suitable for their specific needs.

Analysing qualitative data collected through semi-structured interviews and participant observations, the outcomes of the research were presented in Table 1, which summarizes the sample's characteristics.

Table 1, the sample, coded as "*Participant 1*" (meaning the first participant), was aged between 60 and 85 years, with a mean age of 66.73 years. The mean weight was 58.50 kilograms, the mean height was 157.83 centimetres, and the mean Body Mass Index (BMI) was 23.44. Regarding health issues, the data indicated the presence of hypertension, allergies, and diabetes.

Table 2. Description: mean and standard deviation of basic physical characteristics for the experimental group, including age, weight, height, and body mass index.

Table 3. The research findings on the benefits of exercise for the health of the elderly after the COVID-19 outbreak can be summarized as follows: (1) physical health benefits and (2) mental health benefits.

Table 1. Characteristics of the participants.

Given name	Age (year)	Weight (kg)	Height (cm)	BMI (kg/m^2)	Health Problems
MV.1	84	64	165	23.51	No underlying disease
MV.2	80	71	165	26.08	Hypertension
MV.3	65	50	152	21.64	Hypertension
MV.4	67	49	160	19.14	No underlying disease
MV.5	61	81	161	31.25	No underlying disease
MV.6	66	45	151	19.74	Hypertension
MV.7	61	48	154	21.24	No underlying disease
MV.8	60	54	153	23.07	No underlying disease
MV.9	71	56	160	21.87	Hypertension
MV.10	69	57	154	24.03	No underlying disease
MV.11	67	60	156	24.65	Allergies
MV.12	70	56	150	24.89	Hypertension
MV.13	66	56	156	23.01	No underlying disease
MV.14	66	52	151	22.81	No underlying disease
MV.15	65	52	150	23.11	Hypertension
MV.16	60	49	160	19.14	No underlying disease
MV.17	68	73	163	27.48	Hypertension
MV.18	66	49	156	20.13	Diabetes
MV.19	70	65	165	23.88	Hypertension
MV.20	77	45	150	20.00	No underlying disease
MV.21	73	53	156	21.78	No underlying disease
MV.22	62	67	152	29.00	No underlying disease
MV.23	60	48	147	22.21	No underlying disease
MV.24	62	62	160	24.22	Hypertension
MV.25	60	64	165	23.51	Hypertension
MV.26	64	70	168	24.80	Hypertension
MV.27	65	60	160	23.44	No underlying disease
MV.28	65	62	156	25.48	Hypertension
MV.29	65	68	170	23.53	Hypertension
MV.30	67	70	169	24.51	Hypertension
$\bar{x}$	66.73	58.53	157.83	23.44	

Table 2. Baseline characteristics in the control and experimental groups.

Parameters	EXG (n = 30)
Age (year)	66.73 ± 5.82
Weight (kg.)	58.53 ± 0.926
Height (cm.)	157.83 ± 6.36
BMI(kg/m^2)	23.44 ± 2.73

Table 3. Summary of findings.

Benefits of exercise for health to elderly after the COVID-19 outbreak
(1) Physical health benefits
(2) Mental health benefits

The interview and observation could be described as following:

Physical health benefits

Elderly people have chosen to exercise to improve their health after the COVID-19 outbreak in order to strengthen their physical health and boost their immune system. For example, *MV 2. (80 years old)* said that she has been exercising regularly since the pandemic and has noticed a significant improvement in her overall health. She used to suffer from multiple health conditions, but now she only has high blood pressure, which is well-controlled due to her consistent exercise and health management. *MV 4. (67 years old)* explained that she has been exercising regularly both before and after the COVID-19 outbreak. This has helped her maintain good health, slow down the aging process, improve her mobility, and enhance her digestion and sleep. *MV 7. (61 year old)* shared that since starting her exercise routine, she has felt stronger and healthier. She experiences fewer illnesses, has a healthy heart, and has no muscle aches or pains. Her mobility and breathing have also improved significantly, and she no longer gets tired easily. *MV 10. (69 year old)* regular exercise has had a positive impact on my aunt's health. She reports feeling stronger, more flexible, and experiencing less fatigue. *MV 14. (66 year old)* My aunt has made a conscious effort to prioritize her health, especially after COVID-19. Her consistent exercise routine has significantly improved her physical well-being. She feels stronger, has no muscle soreness, and enjoys working out. *MV 17. (68 year old)* has been working hard to improve her health since recovering from COVID-19. She started slowly and has been making steady progress. Now, she's much stronger and more active. *MV 21. (73 year old)* since recovering from COVID-19, I've been exercising to improve my overall health and well-being. *MV 24 (62 year old)* to improve my health after COVID-19, I've been doing gentle exercises such as walking and stretching. It's a great way to relax. *MV 26 (64 year old)* I've made it a daily habit to exercise since recovering from COVID-19. Health is my top priority, and exercise is a great way to prevent diseases and stay healthy. *MV 28 (65 year old)* since recovering from COVID-19, my aunt has been prioritizing her health by exercising regularly. As a result, she's feeling stronger, healthier, and less prone to illness. Exercise has also improved her flexibility, joint health, and sleep quality.

Mental health benefits

There are various types of exercise suitable for seniors, tailored to their specific needs and interests. These activities not only benefit their physical health but also contribute to their mental well-being. *MV 1 (84 year old)* exercise has become a daily routine for me after COVID-19. It has significantly improved my physical and mental well-being. The feeling of relaxation and peace of mind motivates me to work out every day. *MV 3 (65 year old)* since I recovered from COVID-19, I've been making a conscious effort to take care of my health. Exercising not only keeps me physically fit but also provides a great way to unwind and have fun with friends. It's really helped improve my mental health and overall happiness. *MV 5 (61 year old)* Exercise has become a source of joy and relaxation for me. It helps me to unwind and feel good about myself. I love taking care of my body and mind. *MV 8 (60 year old)* since recovering from COVID-19, I've been focusing on maintaining a healthy lifestyle. Eating nutritious food and exercising regularly have significantly improved my physical and mental health, boosting my immune system. *MV 12 (70 year old)*. Exercise has greatly improved my cardiovascular health. I feel more energized and my mind is sharper. It's like my body and mind are working together in harmony. My blood circulation is better, and my memory has improved significantly. *MV 16 (60 year old)* regular exercise boosts your immune system, prevents muscle aches, and promotes relaxation. By combining a healthy diet with regular workouts, you can maintain optimal physical and mental health. *MV 19 (70 year old)* to strengthen your immune system and maintain good health post-COVID-19, it's essential to prioritize self-care. Regular exercise, a balanced diet, and adequate rest can significantly improve both your physical and mental health. *MV 22 (62 year old)* exercise not only benefits my physical health but also improves my mental well-being. It helps me relax, reduces stress, and even helps me make new friends. It's a great way to unwind and have fun. *MV 25 (60 year old)* walking with her friends has become a fun routine for my aunt. It's great exercise and helps her feel good both physically and mentally. *MV 29 (65 year* *old)* regular exercise after recovering from COVID-19 is crucial for maintaining good health. It helps strengthen the lungs and heart, improves overall physical fitness, and promotes mental well-being.

Analysing the percentage of health problems (1) No underlying conditions (46.67%): This refers to a group of individuals who reported health problems but upon examination, no chronic or pre-existing conditions were found to be the cause. (2) Hypertension (46.67%): This refers to a group of individuals with health issues related to high blood pressure. (3) Allergies (3.33%): This refers to a group of individuals with health issues related to allergic reactions, such as allergies to pollen or food. (4) Diabetes (3.33%): This refers to a group of individuals with health problems related to diabetes.

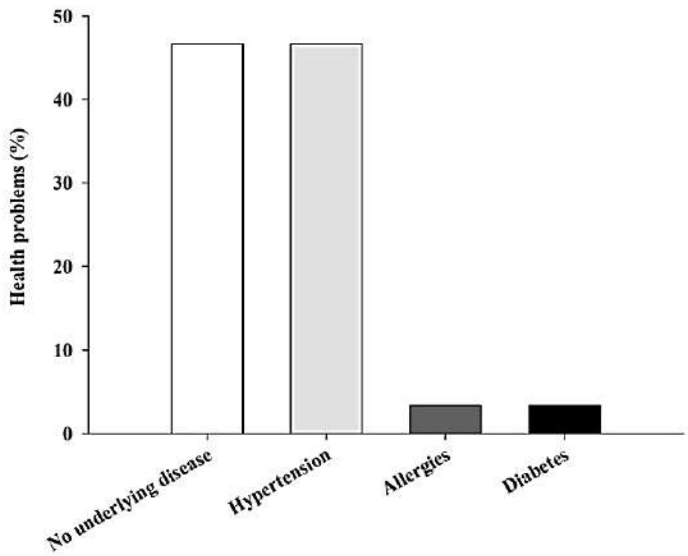

Figure 1. The percentage of health problems included no underlying disease (46.67%), hypertension (46.67%), allergies (3.33%), and diabetes (3.33%).

DISCUSSION

The study on exercise selection for health to elderly post-COVID-19 outbreak found that the elderly have become more aware of and prioritize the importance of selecting appropriate exercises to maintain both physical and mental health. Living a healthy and active lifestyle has been proven to prolong life expectancy (Chudasama et al., 2020; Limpens et al., 2022; Monma et al., 2019). Recently, the World Health Organization (WHO) declared 2020-2030 as the Decade of Healthy Aging, which aims to foster healthy aging and improve the lives of older people (World Health Organization, 2020). The WHO defines healthy aging as "*the process of developing and maintaining the functional ability that enables wellbeing in older age*" (Fallon and Karlawish, 2019; Michel and Sadana, 2017). Regular exercise is one or the ways to achieve a better quality of life in old age. Various sports and exercise can be regularly undertaken by the older adults, ether individually or in groups, to improve physical fitness (Syaukani et al., 2024). As stated by Suryadi et al., (2024) on their literature review, exercise such as yoga, aerobic sports, and resistance training is proved to have beneficial impact to older adults. Physical activities involve the use and combination of various forms of exercise, including Ruesi Dadton Qigong (RSD) and massage to improve body balance. Arm and leg muscle strength, flexibility, shoulder flexibility Cardiovascular system and respiratory system. The aim is to make the elderly have good physical fitness. (Nontakhod et al., 2022). Exercising regularly can maintain and improve immunity in the elderly (Lee et al., 2022b; Park et al., 2023). In light of the lasting effects of the recent coronavirus disease

2019 (COVID-19) pandemic, many elderly individuals have faced disruptions in their lives and health, the continuous practice of exercise is recommended to the older people (Maloir et al., 2018). Focusing on raising awareness of the health benefits of physical activity and its influence in keeping fit may help maintain or increase exercise practice during lockdown period (Suarez Fernandez and Garcia Villar, 2024). However, increased global life expectancy also indicate and accompany better health among overall aging population. With strong emphasis on the health management and well-being at older age, people are aging healthier than ever before (Jee, 2024).

CONCLUSION

Choosing the right exercise for older adult's post-COVID-19 outbreak has significant benefits for both physical and mental health. There are various types of exercises that older adults can engage in. These include walking, stretching, and rhythmic exercises. Therefore, regular physical activity is crucial for the elderly to boost their immune system, protect against diseases like COVID-19, and enhance their overall quality of life.

AUTHOR CONTRIBUTIONS

Kritpech Nontakhod: preparation and research design, data collection, statistical analysis, results interpretation, manuscript writing, supervision of the study, and review of the final version. Kanoot Ratchakit and Poorichaya Krobtong: data collection and reviewed the manuscript. Supamat Ketthaison and Chotika Sremsiri: manuscript writing and supervision of the study. Kampeeraphab Intanoo: review of the final version.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

HUMAN RESEARCH ETHICS

This research was approved by the Human Research Ethics Committee of Buriram Rajabhat University (BRU: 011/2024).

ACKNOWLEDGEMENTS

The author would like to thank the participants that helped and supported this research.

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ORIGINAL ARTICLE

Effects of a six-week plyometric training program on balance, jumping ability, and between-leg asymmetry in young adult basketball players

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ABSTRACT

Improving balance, jumping ability and unilateral actions is of great importance in basketball. The key question is how to get it. Eighteen amateur basketball players (age: 23 ± 2.8 years; height: 185.3 ± 0.064 m; body mass: 85.2 ± 9.9 kg) participated in this study and were divided into the experimental group (n = 10) or a control group (n = 8). The following metrics were recorded one week before and one week after the training program: anthropometric measurements, Y-Balance, Standing Stork, ankle dorsiflexion range of motion, arm-inclusive bilateral-vertical countermovement jump, unilateral 0.2-m drop jump, and Triple-Hop tests. The experimental group underwent a moderate-intensity six-week plyometric training program which included bilateral and unilateral jumps, some performed consecutively and others with rest between jumps. Results indicate that right ankle ROM improve 9.8% (*p* = .012), YBT Right Anterior (6.4%; 0.063) and YBT Left Posteromedial (6.2%; 0.010). In jumping ability, RSI left improve of 18.6% (*p* = .019), DJ Height Left (13.1%; 0.037) and DJ Height Right (11%; 0.025). Regards asymmetry the only statistically significant improvement occurs in the Ankle ROM test, with an improvement of 60.8% (*p* = .017).
Keywords: Performance analysis, Plyometric exercise, Explosiveness, Imbalance, Jump, Strength.

Cite this article as:
Zafón-Chulia, D., Moreno-Mañas, E., & Llana-Belloch, S. (2025). Effects of a six-week plyometric training program on balance, jumping ability, and between-leg asymmetry in young adult basketball players. *Journal of Human Sport and Exercise, 20*(2), 606-619. https://doi.org/10.55860/mbewnn78

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Submitted for publication November 23, 2024.
Accepted for publication January 08, 2025.
Published March 26, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/mbewnn78

INTRODUCTION

Basketball is a team sport that requires a high level of contact and numerous explosive actions and demands multidirectional movement patterns, the majority of which are unilateral (Dos'Santos et al., 2018). Most injuries in basketball take place during these unilateral actions (Bahr and Krosshaug, 2005) and, in case of bilateral actions, in the leg that produces the most strength (Gonzalo-Skok et al., 2017). Understanding asymmetry as the difference in the strength capacity of the lower limbs (Kons et al., 2021; Thomas et al., 2017), it is known that asymmetries of 15% or more result in decreased physical performance and a dangerous increase in the risk of injury (Bishop et al., 2018; Guan et al., 2022; Ličen and Kozinc, 2023). Asymmetry is usually assessed by analysing the hip extensors and flexors and knee extensors with a dynamometer while performing isokinetic and isometric tests (Thomas et al., 2017; McElveen et al., 2010; Bond et al., 2017).

However, lately this aspect has become more important. In fact, many authors even say that one of the key issues raised by the asymmetry is the laterality of the players. For example, right-handed or left-handed players can be affected in a different way when playing and training. Then, the relationships of laterality, technical and tactical drills, or playing systems have a direct impact on asymmetry and the physical practice may affect this development. Also, this issue (more right-handed than left-handed players) may mask the real effects of asymmetry when some of left-handed are forced to solve systems more focused on right/left zones of the court (Fernandez et al., 2009) or when training the tasks are more related to different development of lateral dominance (Stöckel and Carey, 2016). As McElveen indicated, this differences between left and right legs can be diminished by SSC training and multidirectional high-speed movements (McElveen et al., 2010).

Plyometrics train these SSCs, thus helping to enhance the eccentric loading phase energy stores and improve the maximum strength output during the concentric phase of the movement (Booth and Orr, 2016; Asadi et al., 2015; Taube et al., 2012; Komi and Gollhofer, 1997). It is known that plyometric exercises are beneficial to balance (Asadi et al., 2015; Ramachandran et al., 2021; Kobal et al., 2017; Ramírez-Campillo et al., 2015a; Ramírez-Campillo et al., 2015b; McInnes et al., 1995) and jumping ability (Ramírez-Campillo et al., 2015a; Ramírez-Campillo et al., 2015b; Ramírez-Campillo et al., 2022; Balsalobre-Fernández et al., 2015; Ozbar et al., 2014; Sáez-Sáez et al., 2009; Villarreal et al., 2008) and therefore have a positive effect on performance (Ramírez-Campillo et al., 2022; Ziv and Lidor 2010) and injury prevention (Asadi et al., 2015; Ramirez-Campillo et al., 2020; Suchomel et al., 2019; Rhouni et al 2019; Brachman et al., 2017; Filipa et al., 2010; Meylan et al., 2009; Fouré et al., 2009; Myrick 2007; Spurrs et al, 2003; Diallo et al., 2001), although not all studies have shown its effectiveness (Kurt et al., 2023; Meszler and Váczi 2019). Furthermore, jump height is representative of lower-limb strength and power (McElveen et al., 2010; Balsalobre-Fernández et al., 2015; Villarreal et al., 2008) and is a good indicator of neuromuscular fatigue (Balsalobre-Fernández et al., 2015). However, because of the different patterns of movement used in basketball, perhaps only vertical jumps can be used to represent performance, and so the use of multidirectional unilateral tests is recommended when trying to fully profile an athlete's strength (McElveen et al., 2010; Meylan et al., 2009). So, the aim of this study was to examine the effects of a six-week plyometric training (PT) program on different factors that affect basketball performance, such as balance, jumping ability, and between-leg asymmetry in young adult basketball players. We hypothesize that with these kind of training players will improve indicated skills.

MATERIALS AND METHODS

Participants

Eighteen young adult amateur basketball male players from the same team (age: 23 ± 2.8 years; height: 185.3 ± 0.064 m; body mass: 85.2 ± 9.9 kg) were randomly assigned into the control or experimental group (see Table 1). The T-test performed found no differences (*p* > .05) between the two groups for the indicated variables. They all had at least 10 years' experience in competition and had been continuously participating in basketball practice training for the 4 months prior to the study. Twenty volunteer participants were recruited and randomly split into a control group (CG) and an experimental group (EG). During the study, two participants dropped out from the control group and hence group sizes for all reported results are n = 8 (CG) and n = 10 (EG). None of the subjects had previously done systematic PT training. Participants meeting the following criteria were excluded from the study: (a) potential medical problems or a history of knee or ankle injury in the year before study; (b) medical or orthopaedic problems that could compromise their performance in the study; and (c) had received any lower extremity reconstructive surgery in the past 2 years or had unresolved musculoskeletal disorders. Authors declare that the experiments reported in the manuscript were performed in accordance with the ethical standards of the Helsinki Declaration and that the participants signed an informed consent form.

Table 1. Characteristics of the study participants.

Characteristics	**EG (n = 10)**	**CG (n = 8)**
	Mean ± SD	Mean ± SD
Age (years)	23.6 ± 2.4	22.6 ± 2.3
Height (m)	1.86 ± 0.07	1.85 ± 0.04
Body Mass (Kg)	89.6 ± 9.0	88.8 ± 7.7
Body Mass Index (Kg/m^2)	25.8 ± 1.6	25.9 ± 1.7
Body Fat (%)	20.9 ± 5.4	20.9 ± 4.4
Body Muscle (%)	38.7 ± 3.3	39.5 ± 2.1
Leg length right (m)	1.078 ± 0.06	1.011 ± 0.037

Note. EG (experimental group), CG (control group). No differences (p > .05) between the two groups were found for these descriptive variables.

Testing procedures

A six-week PT program performed twice a week between January and March of 2018 (see Table 2). During the study, all the participants followed their normal technical and tactical basketball training, and in addition, the EG also performed PT. The PT sessions lasted 25 to 35 minutes and comprised 10 minutes of specific warm-up and 15 to 25 minutes of PT and were completed between 18:30 and 20:30 on Monday and Wednesday (all in the same time zone and measured by the same researcher). A combination of multilateral, multidirectional jumps were used and performed in a consecutive (without rest between jumps to take advantage of the stretch-shortening cycle) and non-consecutive way, with 15 seconds of rest between jumps (Taube et al., 2012; Ramírez-Campillo et al., 2015b), allowing 60 seconds recovery between sets (Read and Cisar, 2001). In addition, before the PT program started, the EG received 3 sessions to get familiarized with the submaximal and maximal actions comprising the PT exercises to ensure were able to produce a consistent technique.

Two testing session were carried out one week before (pre-test) and one week after (post-test) the PT period. On day 1, the following tests were performed: (a) anthropometric measurements, (b) dynamic balance assessment Y-Balance Test (YBT), (c) static balance assessment Standing Stork Test (SST), and (d) ankle dorsiflexion range of motion (ROM). On day 2, (e) unilateral drop jump (DJ) from 0.2 meters (20-DJ), (f) bilateral countermovement jump (CMJ) with use of the arms, and (g) a Triple-Hop Test (THT) were performed. A stadiometer was used to measure the participants' height and a bioelectrical impedance scale (Omron BF511) to record their body composition and body mass. Before each testing session, both groups performed a specific 10-minute warm-up which consisted of: 5 minutes of submaximal running and mobilization of the joints implicated in the tests and 5 minutes of submaximal jumps (10 vertical-bilateral and 5 vertical-unilateral with each leg, and 10 horizontal-bilateral and 5 horizontal-unilateral with each leg). All the participants were instructed to wear the same shoes and similar clothes on each of the testing days.

Table 2. Program of 6-week plyometric training. 2 sessions per week.

Exercises	**Set × repetitions (mode of execution)**					
	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
Bilateral horizontal	2 × 4 (C) 2 × 4 (N)	2 × 5 (C) 2 × 5 (N)	2 × 6 (C) 2 × 6 (N)	2 × 7 (C) 2 × 7 (N)	2 × 8 (C) 2 × 8 (N)	2 × 9 (C) 2 × 9 (N)
Bilateral vertical	2 × 4 (C) 2 × 4 (N)	2 × 5 (C) 2 × 5 (N)	2 × 6 (C) 2 × 6 (N)	2 × 7 (C) 2 × 7 (N)	2 × 8 (C) 2 × 8 (N)	2 × 9 (C) 2 × 9 (N)
Left horizontal	2 × 4 (C) 2 × 4 (N)	2 × 5 (C) 2 × 5 (N)	2 × 6 (C) 2 × 6 (N)	2 × 7 (C) 2 × 7 (N)	2 × 8 (C) 2 × 8 (N)	2 × 9 (C) 2 × 9 (N)
Right horizontal	2 × 4 (C) 2 × 4 (N)	2 × 5 (C) 2 × 5 (N)	2 × 6 (C) 2 × 6 (N)	2 × 7 (C) 2 × 7 (N)	2 × 8 (C) 2 × 8 (N)	2 × 9 (C) 2 × 9 (N)
Left vertical	2 × 4 (C) 2 × 4 (N)	2 × 5 (C) 2 × 5 (N)	2 × 6 (C) 2 × 6 (N)	2 × 7 (C) 2 × 7 (N)	2 × 8 (C) 2 × 8 (N)	2 × 9 (C) 2 × 9 (N)
Right vertical	2 × 4 (C) 2 × 4 (N)	2 × 5 (C) 2 × 5 (N)	2 × 6 (C) 2 × 6 (N)	2 × 7 (C) 2 × 7 (N)	2 × 8 (C) 2 × 8 (N)	2 × 9 (C) 2 × 9 (N)
Total per leg	64	80	96	112	128	144

Note. C (consecutive), N (Non-consecutive). The order of exercises execution was randomized for each training session. All exercises were executed with the technique described as countermovement with arms.

Y-Balance Test. This test was used to assess dynamic balance and required participants to stand on one leg while extending the contralateral leg as far as possible in each of three different directions (i.e., anterior, posteromedial, and posterolateral; Hammami et al., 2016; Chaouachi et al., 2017). A grid with a 'Y' form was constructed by placing three lines on the floor with adhesive tape marked at 5 mm intervals. The two posterior lines radiated from the centre of the 'Y' with an angle of 45 degrees between them and at 135 degrees with the anterior line. For the normalized measurements, the right leg length of each participant was measured in the supine lying position from the level of the anterior superior iliac spine to the most distal aspect of the medial malleolus of the ankle. Before we started the trial measurements, we allowed the participants to practice, for up to six trials in each direction (three in each leg), to familiarize themselves with the test.

All the trials were carried out barefoot. The participants were allowed to rest bilaterally for 15 seconds between each attempt. The examiner manually noted each distance from the centre of the grid to the most distal point reached. Attempts were discarded and repeated if the participant (a) did not touch the line with the reaching foot while bearing the weight on the stance leg; (b) displaced the stance foot from the centre of the grid; (c) lost balance at any point during the trial; (d) did not maintain the balanced position for 1 second in the start and return positions; or (e) bore the weight on the reaching foot to gain support.

The mean of 3 successful attempts in each direction was used in subsequent analyses. In addition, a composite score (CS) was calculated based on the maximum distance reached for each direction and the length of the right leg (Filipa et al., 2010; Hammami et al., 2016; Chaouachi et al., 2017) using the following formula: CS = [(maximum anterior reach distance + maximum posteromedial reach distance + maximum posterolateral reach distance) ⁄ leg length × 3] × 100.

Standing Stork Test. Static balance was assessed using the SST. Participants initially stood on their left leg, placing their opposite foot against the inside of their supporting knee with both hands placed on their hips. When indicated, the athlete had to raise their heel from the floor and maintain balance for as long as possible. The attempt was considered finished if the participant (a) moved their hands from their hips; (b) the ball of the foot was displaced from its original position; or (c) the heel touched the floor. After three attempts, the legs were switched. Each trial was measured in seconds with a manual chronometer. The best score of the three attempts was recorded for further analysis.

Ankle range of motion. Ankle dorsiflexion ROM was calculated based on the maximal passive flexion and maximal passive extension using the Dorsiflex App for the iPad Air 2 (Balsalobre-Fernández et al., 2015) Participants stood with one knee on the floor with the other leg located in front of them, supported by the sole of the foot. From this position, the participants were asked to flex their forward ankle to the limit first by moving their weight to the front and then extending their ankle by displacing their weight backwards. The Dorsiflex App was calibrated to their shin, thus allowing us to measure the degrees of their flexion and extension and their maximal ankle extension and flexion were recorded and used to calculate the full range of movement.

Vertical jump tests. Two vertical jump tests were used in this study: a CMJ and a 20-DJ; the volunteers were allowed to swing their arms. Furthermore, the participants had to take off with their knees and ankles extended and land in the same position and place to minimize any possible horizontal displacement but were told to flex their knees immediately after touching the ground to soften their landing. All the vertical tests were assessed using the MyJump 2 App for the iPad Air 2, (Balsalobre-Fernández et al., 2015). A rest of 45 seconds was allowed between jumps and at least 5 minutes were allowed between the two jump tests.

For the CMJ test, participants were required to lower themselves as quickly as possible from an erect position to a self-selected depth, followed by a maximal vertical jump. The mean of three trials, with 45 seconds recovery time between each trial, was recorded and used for further analysis.

The 20-DJ was chosen because of all variables that we recorded; it gave us a good estimate of between-leg asymmetry. All the participants started standing unilaterally at a height of 0.2 meters and, to minimize the contact time with the ground and maximize the jump height, were instructed to try to land in the same spot; the volunteers were allowed to freely use their arms to help balance them during the jump. The mean of 2 trials per leg were recorded and 45 seconds recovery was allowed between the trials. During this test we registered the following variables: ground contact time, flight time, and the Reactive Strength Index (RSI): RSI = Jump height / Ground contact time, where height is in meters and time in seconds (Lloyd et al., 2009).

Horizontal jump test. The THT was used to assess the volunteers' horizontal jumping capacity. A tape measure marked at 0.01-m intervals was fixed to the ground, perpendicular to the starting line. Participants were instructed to start standing on one leg, just behind the starting line and perform 3 consecutive maximal jumps forward with the same leg to reach as far as possible in the horizontal plane; the volunteers were allowed to freely swing their arms during the test. The distance was measured from the starting line to the point where the heel landed in the third and final jump. The mean of 2 attempts for each leg was recorded and used for subsequent analyses.

Asymmetry assessment: as indicated Gonzalo-Skok asymmetry was assessed using representative functional performance situations (Gonzalo-Skok et al., 2017). Thus, we chose unilateral tests with SSC to assess power and jumping ability such as the 20-DJ, and THT and unilateral tests to assess static and dynamic balance such as the SST and YBT (Hammami et al., 2016; Mohammadi et al., 2017). The between-leg asymmetry in this study was calculated as the percentage difference between the strong and weak legs, according to the following formula (Bond et al., 2017): Asymmetry = [(Strong leg value – Weak leg value) / Strong leg value] x 100%.

Statistical analysis

All statistical calculations were performed using the statistical software R 3.6.1 (R Core Team, 2019) and package lme4 1.1.21 (Bates et al., 2015). First, we performed a descriptive analysis of all the variables and expressed them as the mean plus or minus the standard deviation (SD). The EG was compared with the CG using mixed linear models for repeated measures with athlete as random effect and moment and group as fixed factors. The diagnostics of these mixed linear models suggested that with significance level (α) set at .05 the assumptions of mixed linear models were met. These assumptions were checked as follows: Gaussianity of residuals was checked with Kolmogorov-Smirnov tests, equality of variances with Levene's test and absence of outliers with Cook's distance. Furthermore, we computed effect sizes (pseudo-R2) and 95% confidence intervals for all effects.

RESULTS

At a 5% significance level, improvements are statistically significant in more than half of the twenty-one balance and jumping ability variables considered: 41.67% of twelve (balance) and 66.67% of nine (jumping ability). Furthermore, slightly increasing the significance level to 6.5% increases substantially the degree of improvement to 58.33% of balance variables and 88.89% of jumping ability variables.

Regarding balance (see Table 3), the most notable improvements resulting from the training occur in the following tests: right ankle ROM, with an improvement in the experimental group relative to the control group of 9.8% (*p*-value = .012), YBT Right Anterior (6.4%; 0.063) and YBT Left Posteromedial (6.2%; 0.010).

In jumping ability (see Table 4), the most notable improvements resulting from the training occur in the following tests: RSI left, with an improvement in the experimental group relative to the control group of 18.6% (*p*-value = .019), DJ Height Left (13.1%; 0.037) and DJ Height Right (11%; 0.025).

Respecting asymmetry (see Table 5), the only statistically significant improvement resulting from the training occurs in the Ankle ROM test, with an improvement in the experimental group relative to the control group of 60.8% (*p*-value = .017). The YBT Anterior test is close to being statistically significant (*p*-value = .055) with an improvement of 65.5%. The DJ Flight Time and THT Asymmetry tests are statistically significant with improvements of 35.7% and 63% respectively but only for the experimental group.

DISCUSSION

This study aimed to assess the effects of a 6-week PT program on balance, jumping ability, and between-leg asymmetry in young adult basketball players. While a statistical analysis of the data concludes that a moderate-volume and frequency plyometric program improves balance and jumping ability in a broad sense, the support for improvements in asymmetry between legs appears to be narrower.

Table 3. Effect of the 6-week plyometric training program on balance.

	Experimental group (EG, n = 10)			Control group (CG, n = 8)			Effect
Balance variables	Pre – Mean ± SD	Post – Mean ± SD	Performance change [|Δ%|]	Pre – Mean ± SD	Post – Mean ± SD	Performance change [|Δ%|]	$\Delta EG - \Delta CG$ [|ΔEG %|] (*p*-value)
YBT Left Anterior (m)	0.738 ± 0.068	0.786 ± 0.056	0.048 [6.5]^(***)	0.742 ± 0.05	0.751 ± 0.046	0.009 [1.2]^◇(***)	0.039 [5.3] (.053)^(*◇(**))
YBT Left Posteromedial (m)	1.056 ± 0.131	1.126 ± 0.125	0.07 [6.6]^(***)	1.045 ± 0.056	1.050 ± 0.049	0.005 [0.5]^◇(***)	0.065 [6.2] (.010)^(**◇(*))
YBT Left Posterolateral (m)	1.113 ± 0.103	1.134 ± 0.063	0.021 [1.9]^◇(***)	1.064 ± 0.037	1.088 ± 0.042	0.024 [2.2]^◇(***)	-0.003 [0.3] (.905)^◇(***)
YBT Right Anterior (m)	0.735 ± 0.078	0.791 ± 0.055	0.056 [7.6]^(***)	0.745 ± 0.052	0.754 ± 0.036	0.009 [1.2]^◇(***)	0.047 [6.4] (.063)^(*◇(**))
YBT Right Posteromedial (m)	1.072 ± 0.131	1.116 ± 0.084	0.044 [4.1]^(***)	1.076 ± 0.054	1.081 ± 0.051	0.005 [0.5]^◇(***)	0.039 [3.6] (.087)^(*◇(**))
YBT Right Posterolateral (m)	1.096 ± 0.094	1.128 ± 0.067	0.032 [2.9]^(***)	1.078 ± 0.044	1.071 ± 0.045	-0.006 [0.6]^◇(***)	0.038 [3.5] (.022)^(**◇(*))
YBT Left CS (%)	0.92 ± 0.065	0.957 ± 0.056	0.037 [4.0]^(***)	0.965 ± 0.056	0.97 ± 0.045	0.005 [0.5]^◇(***)	0.032 [3.4] (.017)^(**◇(*))
YBT Right CS (%)	0.920 ± 0.057	0.955 ± 0.055	0.035 [3.9]^(***)	0.978 ± 0.056	0.973 ± 0.042	-0.005 [0.5]^◇(***)	0.04 [4.4] (.015)^(**◇(*))
SST Left (s)	4.3 ± 1.8	5.8 ± 4.1	1.5 [34.9]^◇(***)	5.5 ± 3.0	5.4 ± 2.4	-0.1 [2.4]^◇(***)	1.6 [37.9] (.242)^◇(***)
SST Right (s)	3.0 ± 0.9	4.8 ± 3.2	1.8 [60.0]^(*◇(**))	4.9 ± 2.5	4.8 ± 2.8	-0.1 [2.5]^◇(***)	1.9 [64.0] (.155)^◇(***)
Left Ankle ROM (º)	82.1 ± 10.1	86.1 ± 9.9	4.0 [4.8]^(*◇(**))	84.2 ± 10.2	84.3 ± 12.2	0.1 [0.1]^◇(***)	3.9 [4.7] (.213)^◇(***)
Right Ankle ROM (º)	78.4 ± 10.0	84.7 ± 9.9	6.3 [8.0]^(***)	84.6 ± 12.3	83.2 ± 12.4	-1.4 [1.7]^◇(***)	7.7 [9.8] (.012)^(**◇(*))

Note. YBT (Y-Balance Test), SST (Standing Stork Test), CS (Composite Score), ROM (Range of Movement). Statistically significant differences are marked at 10% (*), 5% (**) and 1% (***) levels.

Table 4. Effect of the 6-week plyometric training program on jumping ability.

	Experimental group (EG, n = 10)			Control group (CG, n = 8)			Effect
Jump variables	Pre – Mean ± SD	Post – Mean ± SD	Performance change [|Δ%|]	Pre – Mean ± SD	Post – Mean ± SD	Performance change [|Δ%|]	$\Delta EG - \Delta CG$ [|ΔEG %|] (*p*-value)
THT Left (m)	6.194 ± 0.433	6.482 ± 0.380	0.288 [4.6]^(**◇(*))	6.176 ± 0.302	6.020 ± 0.325	-0.156 [2.5]^◇(***)	0.444 [7.2] (.023)^(**◇(*))
THT Right (m)	6.024 ± 0.474	6.476 ± 0.419	0.452 [7.5]^(***)	6.052 ± 0.208	5.859 ± 0.140	-0.194 [3.2]^(**◇(*))	0.646 [10.7] (.000)^(***)
CMJ Bilateral (m)	0.441 ± 0.064	0.484 ± 0.061	0.042 [9.5]^(***)	0.412 ± 0.023	0.409 ± 0.019	-0.004 [0.9]^◇(***)	0.046 [10.4] (.000)^(***)
DJ Height Left (m)	0.234 ± 0.062	0.266 ± 0.047	0.033 [13.9]^(***)	0.191 ± 0.033	0.193 ± 0.031	0.002 [1.0]^◇(***)	0.031 [13.1] (.037)^(**◇(*))
DJ Height Right (m)	0.224 ± 0.062	0.255 ± 0.047	0.031 [13.7]^(***)	0.188 ± 0.030	0.194 ± 0.022	0.006 [3.3]^◇(***)	0.025 [11.0] (.025)^(**◇(*))
Contact Time Left (s)	0.3454 ± 0.0557	0.3386 ± 0.0467	-0.0068 [2.0]^◇(***)	0.3518 ± 0.0373	0.3719 ± 0.0310	0.0201 [5.7]^(*◇(**))	-0.0269 [7.8] (.057)^(*◇(**))
Contact Time Right (s)	0.3547 ± 0.0779	0.3457 ± 0.0525	-0.0090 [2.5]^◇(***)	0.3739 ± 0.0730	0.3735 ± 0.0424	-0.0004 [0.1]^◇(***)	-0.0086 [2.4] (.747)^◇(***)
RSI Left (m/s)	0.7 ± 0.3	0.8 ± 0.2	0.1 [14.3]^(***)	0.6 ± 0.1	0.5 ± 0.1	-0.0 [3.6]^◇(***)	0.1 [18.6] (.019)^(**◇(*))
RSI Right (m/s)	0.7 ± 0.2	0.8 ± 0.2	0.1 [15.2]^(***)	0.5 ± 0.1	0.5 ± 0.1	0.0 [3.9]^◇(***)	0.1 [12.1] (.060)^(*◇(**))

Note. THT (Tripe Hop Test), CMJ (Countermovement Jump), DJ (Drop Jump), RSI (Reactive Strength Index). Statistically significant differences are marked at 10% (*), 5% (**) and 1% (***) levels.

Table 5. Effect of the 6-week plyometric training program on the asymmetry between legs.

	Experimental group (EG, n = 10)			Control group (CG, n = 8)			Effect
Asymmetry variables (%)	Pre – Mean ± SD	Post – Mean ± SD	Performance change [|Δ%|]	Pre – Mean ± SD	Post – Mean ± SD	Performance change [|Δ%|]	$\Delta EG - \Delta CG$ [|ΔEG %|] (*p*-value)
YBT Anterior (m)	0.054 ± 0.041	0.027 ± 0.021	-0.027◇0[49.9]^(**◇(*))	0.018 ± 0.017	0.026 ± 0.019	0.008◇0[48.6]^◇(***)	-0.036◇0 [65.6] (.055)^(*◇(**))
YBT Posteromedial (m)	0.034 ± 0.036	0.038 ± 0.035	0.004◇0[13.1]^◇(***)	0.039 ± 0.021	0.029 ± 0.023	-0.010◇0[26.7]^◇(***)	0.015◇0 [43.9] (.470)^◇(***)
YBT Posterolateral (m)	0.033 ±0.030	0.022 ± 0.018	-0.010◇0[31.5]^◇(***)	0.018 ± 0.014	0.027 ± 0.012	0.008◇0[47.0]^◇(***)	-0.019◇0 [57.5] (.171)^◇(***)
RSI (m/s)	0.98 ± 0.80	0.70 ± 0.46	-0.28◇0[28.4]^◇(***)	1.42 ± 1.13	0.52 ± 0.39	-0.89◇0[63.1]^(**◇(*))	0.62◇0 [62.6] (.226)^◇(***)
DJ Contact Time (s)	0.88 ± 0.48	0.51 ± 0.40	-0.37◇0[41.9]^◇(***)	1.21 ± 0.65	1.00 ± 0.52	-0.21◇0[17.1]^◇(***)	-0.16◇0 [18.4] (.640)^◇(***)
DJ Flight Time (s)	0.56 ± 0.21	0.36 ± 0.24	-0.20◇0[35.7]^(**◇(*))	0.45 ± 0.33	0.38 ± 0.12	-0.07◇0[15.5]^◇(***)	-0.13◇0 [23.2] (.326)^◇(***)
THT Asymmetry (%)	0.036 ± 0.021	0.014 ± 0.010	-0.023◇0[63.0]^(***)	0.031 ± 0.021	0.022 ± 0.013	-0.009◇0[28.6]^◇(***)	-0.014◇0 [38.4] (.180)^◇(***)
Ankle Flexion (º)	7.7 ± 7.2	4.3 ± 4.3	-3.4◇0[44.4]^◇(***)	7.6 ± 4.9	7.1 ± 6.4	-0.5 [6.5]^◇(***)	-2.9◇0 [38.1] (.355)^◇(***)
Ankle Extension (º)	10.5 ± 9.2	5.0 ± 4.7	-5.5◇0[52.1]^(*◇(**))	8.3 ± 8.2	7.9 ± 5.6	-0.4◇0[4.6]^◇(***)	-5.1◇0 [48.5] (.256)^◇(***)
Ankle ROM (º)	8.1 ± 5.1	4.0 ± 3.8	-4.1◇0[50.9]^(***)	4.2 ± 4.0	5.0 ± 2.5	0.8◇0[19.3]^◇(***)	-4.9◇0 [60.8] (.017)^(**◇(*))

Note. YBT (Y-Balance Test), RSI (Reactive Strength Index), DJ (Drop Jump), THT (Tripe Hop Test), ROM (Range of Movement). Statistically significant differences are marked at 10% (*), 5% (**) and 1% (***) levels.

Table 6. Diagnostic analysis.

All variables	**Gaussianity**		**Equal variances**	**Outliers**	**Fit**	
	Shapiro	Kolmogorov	Levene	Cook	R^2_{cond}	R^2_{marg}
YBT Left Anterior	0.19	0.47	0.33	0.26	0.11	0.78
YBT Left Posteromedial	0.93	0.48	0.10	0.24	0.10	0.91
YBT Left Posterolateral	0.00	0.03	0.03	0.41	0.13	0.79
YBT Right Anterior	0.08	0.19	0.08	0.33	0.13	0.69
YBT Right Posteromedial	0.23	0.32	0.01	0.23	0.04	0.88
YBT Right Posterolateral	0.52	0.26	0.10	0.20	0.10	0.90
YBT Left CS (%)	0.41	0.24	0.07	0.17	0.12	0.91
YBT Right CS (%)	0.47	0.43	0.14	0.17	0.16	0.86
SST Left (s)	0.03	0.43	0.41	0.34	0.04	0.57
SST Right (s)	0.00	0.37	0.76	0.26	0.10	0.46
THT Left (cm)	0.28	0.18	0.91	0.39	0.18	0.58
THT Right (cm)	0.50	0.37	1.00	0.26	0.30	0.86
CMJ Bilateral (cm)	0.73	0.23	0.24	0.22	0.28	0.97
DJ Contact Time	0.35	0.87	0.47	0.21	0.20	0.20
DJ Flight Time	0.99	0.93	0.05	0.25	0.11	0.42
Ankle Flexion	0.14	0.55	0.10	0.20	0.06	0.42
Ankle Extension	0.11	0.79	0.34	0.24	0.08	0.26
Ankle ROM	0.37	0.57	0.23	0.16	0.16	0.60
Left Ankle ROM	0.97	0.60	0.10	0.16	0.02	0.83
Right Ankle ROM	0.08	0.19	0.95	0.32	0.06	0.87
YBT Anterior	0.00	0.39	0.26	0.52	0.22	0.30
YBT Posteromedial	0.00	0.28	0.77	0.29	0.02	0.02
YBT Posterolateral	0.28	0.57	0.13	0.19	0.07	0.16
RSI Left (m/s)	0.24	0.31	0.52	0.30	0.30	0.89
RSI Right (m/s)	0.67	0.37	0.57	0.18	0.27	0.90
RSI	0.26	0.62	0.05	0.34	0.16	0.16
THT Asymmetry	0.55	0.67	0.13	0.17	0.23	0.41
DJ Height Left (cm)	0.67	0.39	0.79	0.19	0.32	0.87
DJ Height Right (cm)	0.57	0.23	0.74	0.21	0.27	0.92
Contact Time Left (ms)	0.88	0.25	0.86	0.30	0.07	0.82
Contact Time Right (ms)	0.08	0.18	0.10	0.27	0.04	0.63

Note. YBT (Y-Balance Test), SST (Standing Stork Test), CS (Composite Score), ROM (Range of Movement), THT (Tripe Hop Test), CMJ (Countermovement Jump), DJ (Drop Jump), RSI (Reactive Strength Index).

Plyometrics are a dynamic form of resistance training involving SSCs and, in this case, vertical and horizontal displacements of the centre of gravity, which demands constant postural readjustments (Asadi et al., 2015). In a similar study which also implemented a 6-week PT program using only 0.45-m DJs (Asadi et al., 2015) obtained significant improvements (2.76% to 6.03%) in all directions in a Star Excursion Balance Test (SEBT).

Like our study, Ramírez-Campillo showed that after a 6-week PT the CG but not the EG showed significant improvements on the force platform tests in the medial-lateral direction and posteromedial direction (Ramírez-Campillo et al., 2015a). This might be because of the small sample size or because the participants learned to anticipate the test after having become familiar with it. Significant improvements were found for the left and right legs of the composite score (CS) of the YBT (4% and 3.9%, respectively). The CS is a normalized score that represents the sum of all three directions in relation to the length of the right leg (Filipa et al., 2010; Hammami et al., 2016; Chaouachi et al., 2017; Plisky et al., 2021; González-Fernández et al., 2022; Rafagnin et al., 2023) so and so it can be considered representative of YBT performance improvement because it measures dynamic balance, an important factor in neuromuscular control and injury prevention (Asadi et al., 2015; Plisky et al., 2021; González-Fernández et al., 2022; Plisky et al., 2006; Hegedus et al., 2015; Smith et al., 2015).

On the other hand, static balance did not significantly improve in our study, even though we observed a positive tendency (34.9% in the left leg and 60% in the right). Above all, PT resulted in improvements in static balance (Hammami et al., 2016; Chaouachi et al., 2014), but the SD for this test was relatively high and the sample size was not sufficient to show those results. Plyometrics might also lead to an increase in the ankle ROM because of the eccentric stretching phase and the cushioning phase where the joint is forced to conduct a maximal extension and flexion (Miller et al., 2002). In fact, in the present study, the training had a significant effect on the variable Right Ankle ROM. Miller carried out an 8-week PT intervention in 2 groups: one performing on sand and the other in the water (Miller et al., 2002). The water group showed improvements in plantar flexion and the sand group saw improved ankle dorsiflexion. Thus, plyometrics could reinforce the ankle joints and improve their flexibility, an important factor in ankle injury prevention.

In relation to the effect that PT had on jumping ability, all the participants in our experiment saw an increase in jumping distance and in lower-limb strength. There were significant improvements for the horizontal jumps assessed by the THT and the vertical jumps (CMJ) as well as the 20-DJ performance. This also agrees with most of the results found in studies that previously investigated the effect of plyometrics on jump performance (Ramírez-Campillo et al., 2015a; Ramírez-Campillo et al., 2015b; Ramírez-Campillo et al., 2022; Balsalobre-Fernández et al., 2015; Ozbar et al., 2014; Sáez-Sáez de Villarreal et al., 2009; Villarreal et al., 2008). For instance, Ozbar observed an increase in THT after 8 weeks of PT in football players between aged 15 to 22 years (Ozbar et al., 2014). Villarreal et al. (2008) showed the effects of 1, 2, or 4 day-a-week PT programs and observed that a frequency of 2 days a week resulted in the most efficient boost in performance (Ramírez-Campillo et al., 2015a). Furthermore, we also showed that a combination of vertical, horizontal, bilateral, and unilateral jumps produced better jump outcomes than PT performed in a single-direction aisle or plane (Ramírez-Campillo et al., 2015a; Ramírez-Campillo et al., 2015b). Similar to other studies which used bilateral DJs (Ramírez-Campillo et al., 2015a; Ramírez-Campillo et al., 2015b; Villarreal et al., 2008), our results showed performance improvements in the jump height and RSI (for the left leg significantly) but no reduction in the ground contact time—a factor that is normally reduced in studies which use bilateral DJs (Villarreal et al., 2008).

Lastly, there is very little research on the effects of PT on between-leg asymmetry or to use these functional tests to analyse the asymmetry. Nevertheless, we did show that strength training combining unilateral squats with unilateral 20-DJs and unilateral CMJs for 6-weeks reduced the between-leg asymmetry in maximal unilateral squats. In addition, the between-leg asymmetry variables improve more in the experimental group than in the control group for the most part but most of these differences in improvements fail to be statistically significant. At a 5% significance level, improvements in between-leg asymmetry variables are significant in 10% of the ten variables considered, a smaller percentage than in balance and jumping ability. This contrast appears to be the result of a lack of test power: most asymmetry variables improve for both the experimental and control group. Of these improvements, four are significant in the experimental group: YBT Anterior, DJ Flight Time, THT Asymmetry and Ankle ROM. However, of these four, only Ankle ROM remains significant (p = .017) after accounting for the fact that (systematically smaller) improvements were also observed in these same variables in the control group. This is likely because there is a large variability between measurements in both the experimental and control groups. Further research on the effect of PT on asymmetry, perhaps with either larger samples or more precise asymmetry measurements, is likely needed to address this effect in more detail.

Limitations of this study include the lack of data on injuries. However, in line with Myrick, one might expect that the risk of injury is reduced (Myrick, 2007). Other limitations include a reduced sample size or the nature of procedures and tools, which are not sophisticated or lab tools. Despite not being golden standards, they have been validated.

CONCLUSIONS

In conclusion, we observed a significant improvement in horizontal and vertical jumping ability in the unilateral drop-jump, bilateral countermovement jump, and Triple-Hop Tests, which may translate into improved athletic performance. Additionally, after the plyometric program there was a marked improvement in the passive ankle range of motion. Finally, the EG showed a tendency to reduction in between-leg asymmetry in relation to both horizontal and vertical-plane jumps, in addition to a significance improvement towards reduced asymmetry in the ankle range of motion.

Practical applications

The results of the study have a direct application in basketball training, since they indicate that variables as important as balance and jumping skills can easily be improved: implementing 2 weekly sessions of half an hour in duration, with bilateral and unilateral plyometric exercises, allow a measurable improvement in these important variables that affect both performance and the likelihood of injury.

AUTHOR CONTRIBUTIONS

Daniel Zafón-Chulia was the originator of the idea and primarily responsible for carrying out the experimental phase. He also contributed to the writing of the various sections of the article. Enrique Moreno-Mañas contributed to the critical review of the final text, as well as its editing and submission to the journal. Salvador Llana-Belloch was responsible for the experimental design, data analysis, and revision of the final text.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Scaling corrected lower limb girths in professional male soccer players from different divisions

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ABSTRACT

This study examined the influence of height, bone lengths, and bone diameter on interindividual variability of the corrected thigh (CTG) and calf girth (CCG) in professional soccer players from the First Division, Under-20 (U-20), and Under-17 (U-17), using simple allometric models. Anthropometric data from 109 male players were collected, and a multistep analysis, including Pearson correlation and linear regression, was employed to identify predictor variables. The allometric modelling procedure proposed by Nevill et al. (1992) and Nevill & Holder (1994) was used to determine the best model that allowed for the adjustment of inter individual variability in CTG and CCG. The femur diameter was integrated into simple allometric models, elucidating 50% of the variability in both the CTG and CCG. Height, weight, CTG, and CCG exhibited variations, with first division players demonstrating elevated values. However, after adjusting for the femur diameter using the allometric model, most differences were neutralized. In conclusion, this study established femur biepicondylar diameter as the predominant predictor of CTG and CCG in professional football players (1st Division, U20, U17), and integrating this parameter into a simple allometric model successfully mitigated the impact of body size, enabling appropriate CTG and CCG comparisons within player divisions.
Keywords: Performance analysis, Football, Anthropometry, Allometric models, Soccer, Professional players, Corrected girths.

Cite this article as:
Osorio Gutiérrez, A., Zúñiga Galaviz, U., Gómez Llanes, A., Ortiz Real, J. J., Toledo Domínguez, I. J., Favela Ramirez, C. A., & Coelho-e-Silva, M. J. (2025). Scaling corrected lower limb girths in professional male soccer players from different divisions. *Journal of Human Sport and Exercise, 20*(2), 620-632. https://doi.org/10.55860/w88vgy83

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Submitted for publication November 25, 2024.
Accepted for publication January 10, 2025.
Published March 26, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/w88vgy83

INTRODUCTION

In soccer, agility, speed, and muscular power stand out as essential physical abilities in critical moments of the game, such as sprints during ball disputes, jumping for headers, and powerful shots (Dolci et al., 2020). The development and strengthening of the musculature in the lower extremities play a fundamental role in maintaining optimal performance in the execution of these actions (Ishida et al., 2021). Therefore, a detailed evaluation of this musculature is essential to monitor and enhance the performance of football players (Lovell, R., Towlson, C., Parkin, G., Portas, M., Vaeyens, R., & Cobley, S., 2015). Corrected thigh girth (CTG) and corrected calf girth (CCG) provide an opportunity to analyse the lower limb musculature of soccer players in a practical and reliable manner. However, owing to the heterogeneity in the body size of soccer players (Hazir, 2010; McIntyre, 2005), it is necessary to perform an appropriate scaling adjustment to avoid misinterpretation of the results.

To calculate the corrected girths, it is necessary to measure the perimeter and adjacent skinfold, so that a simple equation removes the adipose tissue, leaving only the muscular circumference of the limb (Martin et al., 1990). This practical approach, which uses localized anthropometric measurements, reflects the mass of the corresponding muscle group. Although corrected circumferences represent a rudimentary estimate of the muscle perimeter of the segment being measured, they have been shown to have a high correlation with muscle mass measured directly in cadavers (Martin et al., 1990). However, despite their practicality and clear reflection of lower limb musculature, the CTG and CCG have been underutilized in soccer (Porta et al., 2023).

Unlike somatotype or body composition expressed in percentages, which provide data in relative terms (Carvajal, 2021), the use of direct anthropometric measurements in their raw form, as in the case of corrected circumferences, requires scaling adjustments to eliminate the effect of body size and allows for appropriate comparisons between individuals of different sizes. In the context of soccer, this is particularly important, as it has been observed that, even within the same team, players exhibit noticeable heterogeneity in terms of their weight and height, largely because of their specialization in different positions in the field (Hazir, 2010; McIntyre, 2005). Furthermore, when comparing players from different divisions, even when they are in close proximity at the competition level, differences in body size tend to be more pronounced, and variations in body composition and somatotype can also be observed (Porta et al., 2023; Zuñiga Galaviz et al., 2018).

There are several methods for adjusting anthropometric variables to eliminate the effects of body size (Almagià et al., 2015). Perhaps the most widely disseminated and employed method among anthropometrists is the "*Phantom*" model (Almagià et al., 2015; Sánchez Martínez et al., 2016). However, although it has been used to analyse specific anthropometric variables in various sports, including soccer (Rivera Sosa, 2006; Hencken & White, 2006; Rodríguez-Rodríguez et al., 2019), its applicability is limited because the "*Phantom*" reference, based on an extensive sample of individuals of both sexes and a wide age range, does not capture the distinctive morphological characteristics of each athlete type. Thus, the results obtained using this method lack representativeness (Cabañas Armesilla et al., 2008). On the other hand, allometric models have notable advantages (Nevill et al., 2005). Several studies have demonstrated that allometric models are more suitable for removing the effects of body size on morphological variables (Dewey et al., 2008; Jaric et al., 2005; Nevill et al., 2005; Nevill & Ramsbottom, 1992). Furthermore, this approach allows for predictions with a small margin of error in variance, resulting in a more precise fit than other methods (Nevill et al., 2005). Specifically, in the context of adjusting corrected thigh and calf circumferences, this method is convenient because the increase in muscle mass does not follow a linear relationship with body size (Nevill, Markovic, et al., 2004); allometric relationships are expressed as power functions and are fitted in a nonlinear form on the original scale of the data.

Corrected thigh girth (CTG) and corrected calf girth (CCG) can simplify the assessment of the lower limb musculature of soccer players, but it is crucial to consider body size to avoid incorrect interpretations resulting from interindividual differences. Therefore, this study aimed to examine the influence of height, bone lengths, and bone diameters on the interindividual variability of CTG and CCG in professional soccer players from the 1st Division, Under-20 (U-20), and Under-17 (U-17), using simple allometry models.

MATERIALS AND METHODS

Participants

The study population consisted of 109 male professional soccer players distributed across three categories: 1st Division (n = 43), U20 (n = 34), and U17 (n = 32). At the time of the study, all participants were duly registered with clubs affiliated with the Mexican Football Federation (FMF) and had actively participated in training and official competitions for a minimum of one year. The experiments detailed in the manuscript were conducted in adherence to the ethical standards outlined in the Helsinki Declaration. Prior to their inclusion in the study, all participants willingly signed a consent form, demonstrating their voluntary involvement and comprehension of the research objectives and procedures.

Procedures

This study was conducted two weeks after the conclusion of the tournament in each division. The intention was to prevent any interference with the training schedules established by the physical trainer and coach during the competition period, and to ensure that players would retain the necessary lower limb muscle development for optimal performance. Anthropometric measurements were conducted over a three-day period for each division. Height, sitting height, limb length, and bone diameter were considered potential size predictors influencing the CTG and CCG. To nullify the influence of body size and enable pertinent comparisons of CTG and CCG among players, a simple allometric model incorporating the most robust size variables was employed. The adoption of a cross-sectional study design facilitated the capture of a singular moment in time, providing a nuanced snapshot of players' physical characteristics.

Anthropometric measurements were carried out by two level II certified anthropometrists from the International Society for the Advancement of Kinanthropometry (ISAK). All anthropometric measurements were conducted according to the protocols established by ISAK. Height and sitting height were measured with an accuracy of 0.1 cm using a portable SECA 213 stadiometer (Hanover, MD, USA). Body weight (BM) was recorded with an accuracy of 0.1 kg using a digital scale (model 770, SECA, Hanover, MD, USA). Skinfold thickness measurements were performed using a Slim Guide skinfold calliper with a sensitivity of 0.5 mm. Lengths were measured with an accuracy of 0.5 mm using a Rosscraft segmometer (Blaine, Washington, United States). Diameters were recorded with an accuracy of 1.0 mm, using a long-arm anthropometer to measure the biiliocristal diameter and a short-arm anthropometer for the femur diameter, both from Rosscraft (Blaine, Washington, United States). Mid-thigh and maximum calf circumferences were measured with an accuracy of 0.1 cm using a metal Lufkin anthropometric tape (Maryland, United States).

The Sum of Six Skinfolds (SP6P) was determined by calculating the sum of skinfold thickness measurements at the triceps, subscapular, supraspinal, abdominal, anterior thigh, and medial leg sites, measured in millimetres, dividing it by the player's height in centimetres, and adjusted by the Phantom height, following the formula proposed by Ward et al. (1989): SP6P = (∑tri+sub+se+abd+ma+pm) 170.18/height (cm).

The corrected circumferences were calculated following the assumptions described by Martin et al. (1990). In this approach, it is assumed that tissues have circular and concentric shapes. The corrected muscular circumference (CMC) is calculated as CMC = G × 2π × d, where 'd' combines skin thickness and adipose tissue, and 'G' represents the thigh or calf circumference. Furthermore, it is assumed that the skinfold calliper reading ('S') is twice the thickness of adipose tissue, allowing for the calculation of CMC = G × π × S.

Statistical analysis

Statistical analyses included the calculation of descriptive statistics such as means and standard deviations for age and anthropometric variables. Furthermore, one-way analysis of variance (ANOVA) was performed to compare these variables between the 1st Division, U20, and U17 groups.

A multistep analysis was conducted to identify potential predictor variables for adjusting the corrected thigh (CTG) and calf (CCG) girth. First, Pearson correlation coefficients were calculated to explore the relationships between corrected girths and potential predictor anthropometric variables such as height, sitting height, lengths, and diameters. Subsequently, linear regression analysis was used to identify variables that could serve as predictors for the adjustment of the corrected girths. Finally, the allometric modelling procedure proposed by Nevill et al. (1992) and Nevill & Holder (1994) was used to determine the best model that allowed for the adjustment of inter-individual variability in CTG and CCG. Initially, the following equation based on the power function model was used:

$$Y = a \cdot xk \cdot e$$

Next, to linearize the power function model, logarithmic transformation was applied. In this equation, 'y' refers to CTG or CCG, and 'k' represents the anthropometric descriptor.

$$\log y = \log a + k \log x + \log e$$

Once both the adjustment anthropometric variable and exponent derived from the simple allometric model were obtained, the adjustment of corrected circumferences was performed by dividing the value of the corrected girth (y) by the adjustment anthropometric variable (x) raised to the power of the exponent derived from the simple allometric model (k):

$$\text{Adjusted Corrected Circumference} = y / x^k$$

Statistical analyses were performed using SPSS (version 20.0; (SPSS Inc., IBM Company, New York, USA) and GraphPad Prism (version 5.00 for Windows, GraphPad Software, San Diego, California, USA, https://www.graphpad.com/).

RESULTS

Comparisons of age, sum of the six skinfolds, and basic anthropometric measurements are detailed in Table 1. It is worth noting that 1st Division players exhibited significantly higher mean height and weight than the U17 category soccer players. Table 2 shows that the 1st division players had higher values in terms of bone diameters, such as the biiliocristal and femur, compared to the U17 and U20 players. Significant differences in thigh and calf circumferences were also observed (Table 3).

The correlations between height, limb length, and bone diameter with corrected thigh and calf girth are detailed in Table 4. In the overall analysis of the three groups, a moderate correlation was observed between height and the CTG, and CCG. However, when examining each group separately, only 1st Division players showed a significant correlation between height and CTG and CCG. In contrast, none of the lower limb lengths showed a correlation with CTG or CG in any group. It is important to highlight that femur diameter stood out as the most influential factor in explaining the observed variability in CTG and CCG, both in the combined analysis of all groups and the individual analysis of each group. Importantly, femur diameter maintained a significant correlation in all three groups when analysed separately.

Table 1. Mean comparisons of age, basic measurements, and proportional sum of six skinfolds between 1st division, U-20 and U17 groups.

	1st.Div. (n = 43)	**U-20 (n = 34)**	**U-17 (n = 32)**	**ANOVA**	
	X ± SD	**X ± SD**	**X ± SD**	F	Sig.
Age (yr)	25.66 ± 4.30	18.95 ± 1.43	16.36 ± 0.80	70.91	.000
Stature (cm)	173.90 ± 6.24	173.86 ± 7.22	168.41 ± 5.00	5.91	.001
Sitting height (cm)	90.95 ± 2.78	89.40 ± 2.69	87.04 ± 2.79	5.64	.002
Body mass (kg)	74.62 ± 9.03	66.60 ± 8.65	61.90 ± 6.74	19.09	.001
*PS6S (mm)	53.43 ± 16.25	52.93 ± 18.48	50.85 ± 15.26	0.212	.888

*Note. *PS6S = Proportional sum of six skinfolds (triceps, subscapular, biceps, iliac crest, front thigh and medial calf).*

Table 2. Mean comparisons of lengths and breadths between 1st division, U-20 and U17 groups.

	1st.Div. (n = 43)	**U-20 (n = 34)**	**U-17 (n = 32)**	**ANOVA**	
	X ± SD	**X ± SD**	**X ± SD**	F	Sig.
Ilioespinal height (cm)	96.42 ± 4.68	96.08 ± 4.36	93.74 ± 3.36	1.77	.160
Trochanteric height (cm)	90.71 ± 4.47	90.37 ± 4.09	87.92 ± 3.99	1.87	.141
Trochanteric-tibial lateral length (cm)	44.83 ± 2.57	44.12 ± 2.49	42.86 ± 2.83	1.57	.204
Lateral tibial height (cm)	46.12 ± 2.39	46.10 ± 1.98	45.45 ± 1.89	1.08	.362
Tibiale mediale-sphyrion tibiale (cm)	38.46 ± 1.97	37.79 ± 2.20	37.17 ± 1.77	1.70	.174
Biiliocristal (cm)	28.10 ± 1.19	27.38 ± 1.14	26.28 ± 1.14	7.42	.000
Femur (cm)	10.14 ± 0.409	9.62 ± 0.65	9.63 ± 0.44	10.20	.000

Table 3. Mean comparisons of girths and corrected girths between 1st division, U-20 and U17 groups.

	1st.Div. (n = 43)	**U-20 (n = 34)**	**U-17 (n = 31)**	**ANOVA**	
	X ± SD	**X ± SD**	**X ± SD**	F	Sig.
Thigh (mid tro-tib-lat) (cm)	54.15 ± 3.58	50.10 ± 3.91	49.40 ± 3.06	17.99	.000
Calf (maximum) (cm)	37.20 ± 2.52	35.24 ± 2.17	34.80 ± 2.31	10.40	.000
CTG (cm)	51.58 ± 3.60	47.41 ± 3.74	46.66 ± 3.09	20.55	.000
CCG (cm)	35.43 ± 2.49	33.03 ± 2.02	32.50 ± 2.41	16.54	.000

*Note. CTG: Corrected Thigh Girth (Thigh mid.tro.tib.lat – PI * Front thigh skinfold/10). CCG: Corrected Calf Girth (Calf maximum – PI * Medial calf skinfold/10)*

Tables 5 and 6 summarize the results of the simple allometric model that incorporates the femur diameter as a size descriptor for corrected thigh girth (Table 5) and corrected calf girth (Table 6). The results revealed that by including the femur diameter in the simple allometric model, it was possible to explain 50% of the variance in both the CTCG and CCG. The exponents derived from the allometric analysis using the femur diameter as the adjustment variable were 1.26 CTG and 1.20 CCG. These values indicate that an increase in the bi-epicondylar diameter of the femur has a more pronounced effect on the increase in thigh and calf girths than would be expected in a linear relationship.

Table 4. Correlation coefficients between corrected thigh girth, corrected calf girth and stature, sitting stature, lengths, and circumferences.

	Stature	**Sitting height**	**Ilioespinal height**	**Trochanteric height**	**Trochanteric-tibial lateral length**	**Lateral tibial height**	**Tibiale mediale-phyrion tibiale**	**Biiliocristal**	**Femur**
1st.Div. (n = 43)									
CTG	0.492**	0.149	-0.063	0.109	0.080	0.092	0.309	0.507*	0.683**
CCG	0.417**	0.177	0.051	0.124	-0.016	0.232	0.337	0.491*	0.575**
U-20 (n = 34)									
CTG	0.075	0.231	0.142	0.241	0.198	0.241	0.111	0.298	0.299*
CCG	0.207	0.358*	0.223	0.281	0.121	0.196	0.137	0.124	0.459**
U-17 (n = 32)									
CTG	0.059	0.336	-0.177	-0.038	-0.073	-0.028	-0.366	0.262	0.602**
CCG	-0.126	-0.063	-0.368	-0.294	-0.055	-0.362	-0.414*	0.285	0.712**
Total Sample (n =109)									
CTG	0.360**	0.453**	0.136	0.233	0.233	0.159	0.210	0.558**	0.715**
CCG	0.352**	0.383**	0.271	0.137	0.201	0.181	0.16	0.510**	0.698**

*Note. * p < .05. ** p < .01. CTG: Corrected Thigh Girth (Thigh mid.tro.tib.lat – PI * Front thigh skinfold/10). CCG: Corrected Calf Girth (Calf maximum – PI * Medial calf skinfold/10)*

Table 5. Bivariate correlations and simple allometric models between CTG and femur breadth (n = 107).

X_i size descriptor	**Correlations between CTG and femur X_i**			**Simple alometric model (ln (CTB) = ln (a) + k_i × ln (X_i) + log (ε))**						**Correlation (X_i, CTG/X_i^k)**
							Model summary			
	r	95% CI	Qualitative	a	k_i value	95% CI	R	R^2	*p*	
Femur breadth	0.715	0.608 to 0.797	Very large	1.02	1.256	(1.016 to 1.495)	0.712	.507	< .01	-0.004

Note. CTG Corrected thigh girth, r correlation coefficient, 95% CI 95% confidence intervals, ki scaling coefficient, ε error, a constant, R2 Explained variance.

Table 6. Bivariate correlations and simple allometric models between CCG and size femur breadth (n = 106).

X_i size descriptor	**Correlations between CCG and femur X_i**			**Simple alometric model (ln (CCG) = ln (a) + k_i × ln (X_i) + log (ε))**						**Correlation (X_i, CCG/X_i^k)**
							Model summary			
	r	95% CI	Qualitative	a	k_i value	95% CI	R	R^2	*p*	
Femur breadth	0.698	0.586 to 0.785	large	0.761	1.206	(0.971 to 1.441)	0.706	0.499	< .01	0.002

Note. CCG Corrected calf girth, r correlation coefficient, 95% CI 95% confidence intervals, ki scaling coefficient, ε error, a constant, R2 Explained variance.

Figure 1 illustrates the relationship between the femur diameter and CTG and CCG (panels a and c). It is evident that there was a strong correlation in both cases. On the other hand, although height showed a moderate correlation with CTG and CCG (panels b and d, respectively), the data showed considerable dispersion. Finally, panels e and f demonstrate the effectiveness of the simple allometric models that incorporate femur diameter in the evaluation of CTG (panel e) and CCG (panel f), independent of body size.

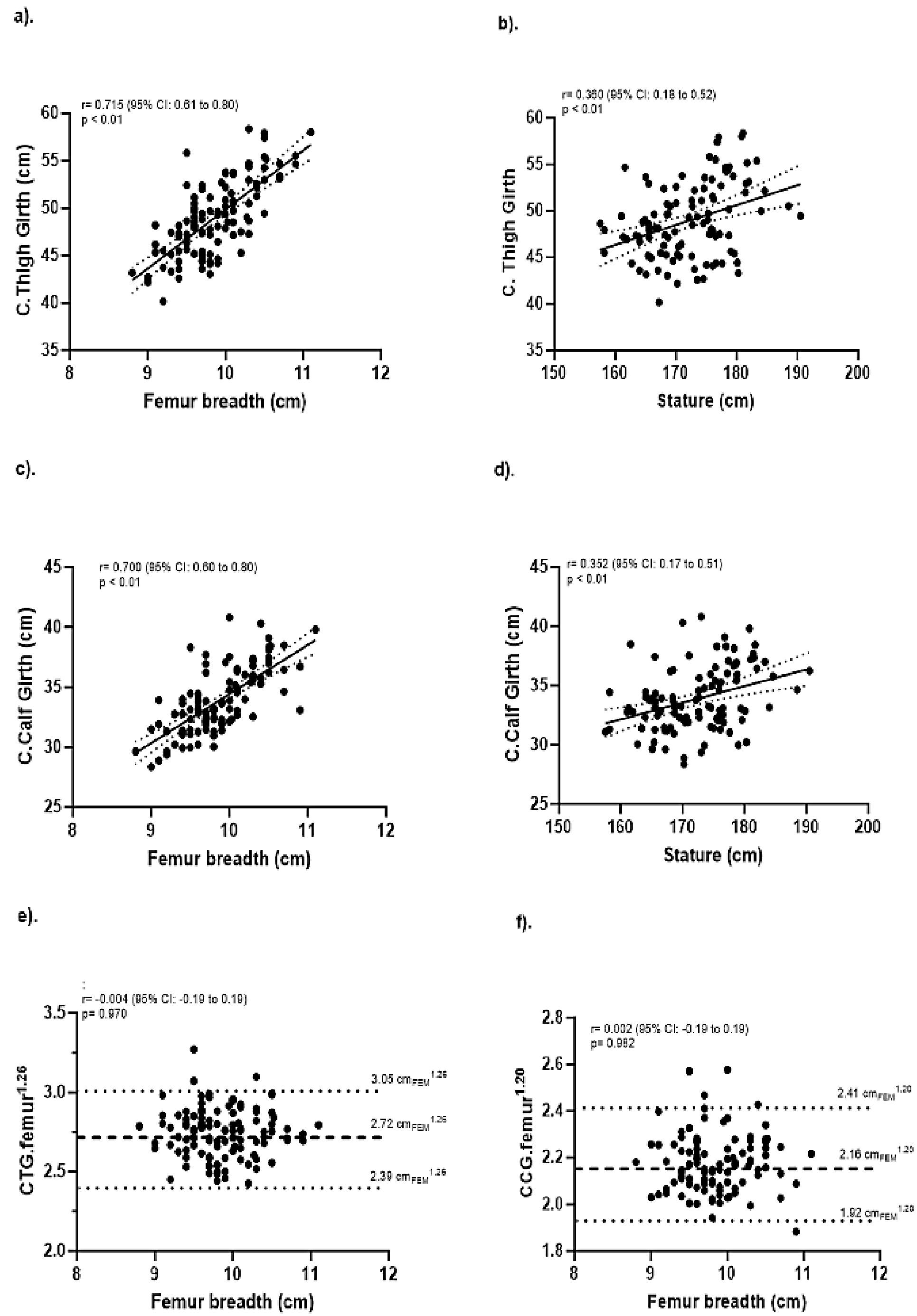
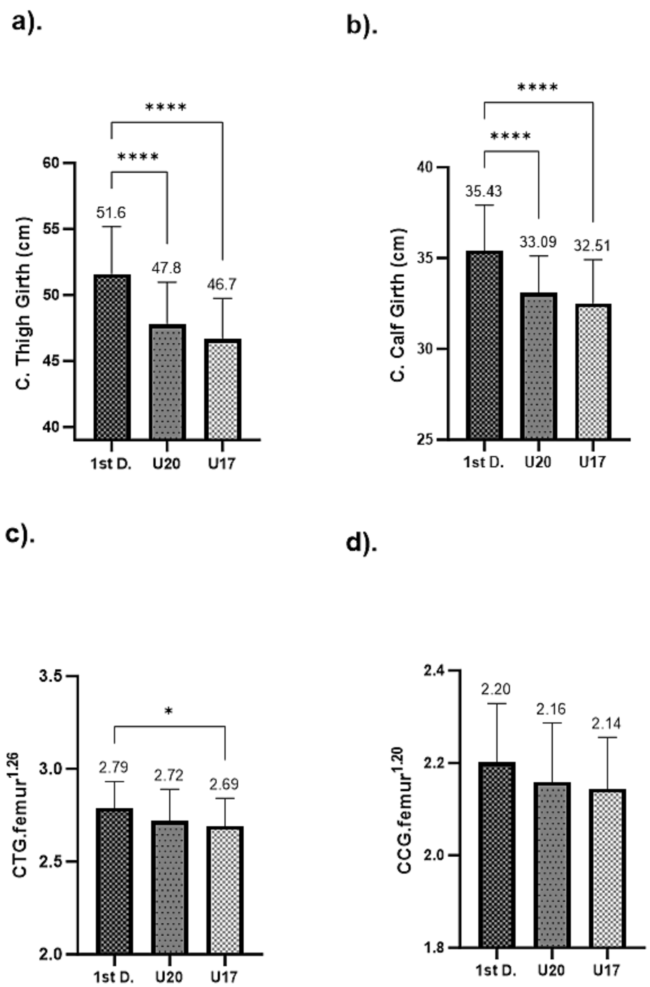


Figure 1. Relationship of Corrected Thigh Girth to Femur breadth (**a**), and to Stature (**b**); relationship of Corrected Calf Girth to Femur breadth (**c**), and to Stature (**d**); and correlations between power functions and respective size descriptors for Corrected Thigh Girth (**e**) and for Corrected Calf Girth(f).

When comparing CTG and CCG in absolute terms between the 1st Division, U20, and U17 groups, it can be seen that in both variables, 1st Division players exhibit significantly higher values compared to the U20 and U17 groups (refer to Figure 2, panels a and b). However, after proper adjustment and comparison of CTG and CCG between the three divisions using the exponents derived in this research through the "*power function ratio standard*" method, disparities are neutralized in most cases. Significant differences between the 1st Division and the U17 category regarding CTC persisted, although their magnitudes significantly decreased (Figure 2, panels c and d).



*Note. **** p < .001; * p < .05.*

Figure 2. Mean and standard deviations values by division groups for corrected thigh girth (**a**), and corrected calf girth (**b**). Means and standard deviations by division groups for scaled CTG expressed per unit of femur (**c**), and scaled CCG expressed per unit of femur (**d**).

DISCUSSION

In the present study, we analysed the influence of height, length, and bone diameter of the lower limbs on the inter-individual variability of corrected thigh girth (CTG) and corrected calf girth (CCG) in professional football players from the first division, U20, and U17 categories. The data showed that players in the first division had higher values of height than U17 players, along with a higher body weight, larger bone diameters, and more prominent thigh and calf circumferences than U20 and U17 players. The best predictor of CTG and CCG was the femur diameter, which explained 50% of the variance in both girths. By incorporating the femur diameter into a simple allometric model, the coefficients of 1.26 for CTG and 1.20 for CCG were obtained. Finally, when comparing the corrected circumferences between the three divisions using the respective exponents with the "*power function ratio standard*" method, the differences between the three divisions are nullified.

Football players undergo morphological and functional changes as they prepare for higher levels of competition, enabling them to achieve optimal performance in elite divisions (Porta et al., 2023). Even before reaching the highest level of competition, players have been observed to show differences in body composition and size after adolescence. For example, in a previous study, a gradual increase in lean body mass was noted in U18 and U21 players (Nikolaidis & Karydis, 2011). These findings align with those of the current study, in which players in the first division exhibited higher values in terms of weight, corrected thigh and calf circumferences, and bone diameters (biiliocristal and femur) than U17 and U20 players. Furthermore, players in the first division had a significantly greater average height than U17 players (refer to Table 1).

Although height is commonly used to control for the influence of body size when assessing various anthropometric variables (Saco-Ledo et al., 2022), the results of this study suggest that height is not the most suitable choice as an adjustment variable for CTG and CCG. Despite the moderate correlation observed between these variables when analysing all three groups together, the correlation analysis conducted separately for each group revealed that only first-division players showed a significant correlation between height and CTG and CCG. Figures 1b and 1d show that although there is a significant correlation between height and CCM and CCP, the data dispersion is wide. These results are not surprising because even among athletic groups, human individuals do not always exhibit similarity in anthropometric proportions influencing height (Nevill, Stewart, et al., 2004). Height is composed of the lengths of the lower limbs and trunk, and the proportion of these body segments varies significantly among individuals. In general, taller individuals tend to have longer lower limbs than their trunk length (Nevill, Stewart, et al., 2004). Nevertheless, even in individuals of similar height, variations in the proportion between the length of their lower limbs and trunk can be observed.

In contrast, the biepicondylar diameter of the femur is directly related to the development of thigh and calf musculature. For example, a wide diameter of the femoral epicondyles implies a wider configuration of the proximal tibial epiphysis at the knee joint. Tendons of the thigh and calf musculature attach around these bony structures to establish their points of origin and insertion. The advantage of wide insertion lies in the ability of the muscles to evenly distribute the force generated across a more extensive area of the bone. This tension distribution may contribute to more effective muscle development (Avin et al., 2015). The results of the current study revealed that femur diameter was the most influential factor in explaining the observed variability in CTG and CCG, both when considering the data of all groups together and when examining the groups individually. Femur diameter emerged as the only variable that maintained a significant correlation in all three groups when analysed separately (see Table 4).

The results of this study showed that by incorporating femur diameter into a simple allometric model, 50% of the variance in both the CTG and CCG could be explained (see Tables 5 and 6). These results demonstrate that this model is an effective predictor of corrected circumferences and is suitable for counteracting the effects of body size. In this context, Figure 1 shows that the correlations between "*scaled CTG*" and femur (panel e) and "*scaled CCG*" and femur (panel f) were virtually insignificant, indicating that the adjustment was effectively made.

The exponents were derived from the allometric analysis using femur diameter as an adjustment variable were 1.26 for CTG and 1.20 for CCG (see Tables 5 and 6). These exponents indicate that an increase in the biepicondylar diameter of the femur has a more pronounced effect on the increase in thigh and calf girths than expected in a linear relationship. The relationship between femur diameter (considered as the size variable in the current study) and the girths of the thigh and calf corresponds to the findings reported by Nevill et al. in 2004. They observed that larger-bodied football players exhibited disproportionately greater growth in leg muscle perimeter. The authors analysed the relationship between corrected thigh and calf circumferences and body mass using an allometric model and obtained exponents of 0.39 and 0.43, respectively. These allometric exponents differ from the predictions of the "*geometric similarity*" theory, which states that the proportional growth between two structures (one linear and one three-dimensional, in this case) should follow a 1/3 scale relationship, thus expecting an exponent of 0.33. The exponents identified by Neville et al. in 2004 are in line with previous findings (Nevill et al., 2003) and, as in our current study, support the idea of disproportionate growth in leg muscle mass in larger individuals (Nevill, Markovic, et al., 2004), or those with wider bone structures, as evident from our results.

When analysing the absolute measurements of CTG and CCG among player groups from the first division, U20, and U17, it became evident that first-division players exhibited significantly higher values for both variables than the U20 and U17 groups (see Figure 2, panels a and b). However, after appropriate correction and comparison of CTG and CCG between the three divisions using the exponents derived from this study via the "*power function ratio standard*" method, most of the disparities are levelled. The only differences between the first division and the U17 category in terms of CTG persisted, although their magnitude decreased significantly (see Figure 2, panels c and d). The fact that the values of the adjusted corrected girths in the U17 and U20 players are comparable to those of the first division (considering the latter as a reference or ideal standard) suggests that the younger groups have undergone adequate muscular development in the thigh and calf regions. This provides evidence that muscles in these areas respond to training, as expected, considering individual bone structures.

While the present study successfully achieved its goal of examining the impact of various anthropometric variables on corrected circumferences, it comes with certain limitations to be considered. It is important to note that the calculation of corrected circumferences assumes a circular geometry for thigh and calf perimeters, despite the inherently more complex anatomy of the lower limbs, which does not perfectly conform to a circular shape. However, it must be noted that this approach benefits from existing research that supports a substantial correlation between corrected circumferences and muscle mass [8]. Furthermore, the cross-sectional nature of this study does not allow us to clarify whether the higher values of height, femur diameter, CTG, and CCG observed in first-division players represent a unique feature of this level, possibly the result of specific selective processes; conversely, younger football players in the U17 and U20 categories will eventually reach these values as they age and advance in their competitive level.

This study's results have several practical implications. First, monitoring the musculature of the lower limbs through corrected thigh and calf girths adjusted by the femur diameter can be used to assess the progress and effectiveness of players' training programs, allowing for personalized adjustments based on their individual characteristics. Furthermore, when evaluating young athletes, measuring bone diameter could be a valuable indicator to identify individuals with greater potential for lower limb muscle development, which, in turn, could influence their future performance capacity in sports that require strength and power. Additionally, the relationship between femur biepicondylar diameter and lower limb muscle development may have significant implications for injury prevention; athlete who do not exhibit optimal muscle development relative to their bone diameters may be at a higher risk of injuries, which can be easily detected using this approach. Future research should validate this hypothesis.

CONCLUSIONS

The results of the present study confirmed that in professional football players from the first division, U20, and U17 categories, the biepicondylar diameter of the femur is the most robust predictor of corrected thigh girth (CTG) and corrected calf girth (CCG) in professional football players from the first division. Incorporating this diameter into the simple allometric model effectively neutralizes the effect of body size, allowing for appropriate comparisons of CTG and CCG among football players in these divisions. In contrast, the height and length of the lower limbs were not good predictors of CTG and CCG.

AUTHOR CONTRIBUTIONS

Research concept and study design: AOG and MCS. Literature review: AOG, UZG, AGLI, IJTD, and CAFR. Data collection: UZG, AOG, and JJOR. Data analysis and interpretation: AOG, UZG, and AGLI. Statistical analyses: AOG and AGLI. Writing of the manuscript: AOG, AGLI, UZG, and JJOR. Reviewing/editing a draft of the manuscript: MCS, CAFR, IJTD, and UZG.

SUPPORTING AGENCIES

The authors acknowledge the financial support provided by the ITSON PROFAPI 2023 program, which was essential for the development and execution of this study.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ACKNOWLEDGMENTS

The authors thank the technical staff and players for their participation and cooperation. Special gratitude to Professor Arturo Osorio Guerrero for his guidance during data collection and for sharing his football expertise, which greatly enhanced the study's efficiency.

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ORIGINAL ARTICLE

Acute effects of high intensity interval training with step aerobics training on cognitive performance in male futsal players

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ABSTRACT

Previous studies have shown that success in sports, especially futsal is linked to higher levels of cognitive functioning. It is widely recognized that short-term, high intensity interval training exercise enhances cognitive function. Nevertheless, the impact of short-term, high-intensity aerobic exercise combined with step aerobics on cognitive function remains unclear. Thus, we aimed to evaluate the acute effects of sport-specific high-intensity interval training with step aerobics training on cognitive in professional futsal players. Here we assess cognitive performance before and after engagement in a high-intensity interval training with step aerobics exercise (HIITSA) regimen. Fifteen male futsal players aged 18-22 years were randomly assigned to one of two experimental groups: (a) an acute high-intensity with step aerobics exercise (n = 8) or (b) a non-exercise control (n = 7). Our findings show that participants in the exercise group demonstrated enhanced performance in cognitive processing tasks ($p \leq .05$). In contrast, control participants who did not engage in exercise showed no significant change over time in cognitive performance ($p \leq .05$). Additionally, we observed that there was no significant muscle hypertrophy following the HIITSA training over a 4-week period ($p \leq .05$). In conclusion, indicate that a brief training period incorporating HIITSA sessions promoted as a time-efficient enhance cognitive performance in elite young futsal players.
Keywords: Performance analysis, Cognitive performance, High intensity interval training, Step aerobics training, Futsal players.

Cite this article as:
Bumrung, N., Jansupom, C., Rohmansyah, N. A., Khaothin, T., Phonthee, S., & Hiruntrakul, A. (2025). Acute effects of high intensity interval training with step aerobics training on cognitive performance in male futsal players. *Journal of Human Sport and Exercise, 20*(2), 633-643. https://doi.org/10.55860/ra1px752

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Submitted for publication January 07, 2025.
Accepted for publication February 21, 2025.
Published March 26, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/ra1px752

INTRODUCTION

Cognitive factors encompass the characteristics of an individual that influence both performance and the learning process. These factors are integral in modulating cognitive function and overall brain performance (Danili & Reid., 2006). Cognitive factors strongly impact athletic performance by influencing the execution of motor skills, attention, and decision-making in a match (Filgueiras et al.,2023). Most recently, evidence suggests that cognitive flexibility were linked to levels of competitiveness in athletes, especially in futsal is linked to higher levels of cognitive functioning (Filgueiras et al.,2023; Arslan et al.,2022). Futsal players depend on working memory to interpret complex strategic plans and adapt to rapidly changing game conditions in real time, a necessity driven by the sport's fast-paced nature (Sehrish Shiraz et al., 2024).

High-Intensity Interval Training (HIIT), a training approach characterized by brief intervals of intense physical activity followed by short recovery or low-intensity periods, at intensities ranging from 80–95% of maximum heart rate or 80–90% of VO_{2max} (Neves et al., 2023), has garnered considerable attention for its capacity to induce substantial improvements in both physiological function and neural adaptations in a relatively short time frame (Atakan et al.,2021; Gómez et al.,2023; Arslan et al.,2022). It is widely accepted that it has gained popularity as a time-efficient method.

Previous studies have shown that high-intensity exercise also seems to increase brain-derived neurotrophic factors (BDNFs), a molecule important for synaptic connections and learning and memory (Fernandez-Rodriguez et al., 2022; Vaynman et al.,2004), Additionally, Step Aerobics (SA), which involves rhythmic movement patterns, involves a variety of movements that are relatively complex by stepping up and down, turning, dancing, and various other coordinated movements with (Charee etal.,2022; Behrens et al.,2017), has shown potential in enhancing spatial awareness and memory development (Hewston et al.,2021).

Numerous studies have proposed that brain-derived neurotrophic factor (BDNF), a key protein involved in neuroplasticity and brain health, plays a crucial role in cognitive enhancements following acute exercise. BDNF supports the survival and growth of neurons, and exercise has been shown to elevate its levels, thereby fostering neural connections that may improve cognitive function. The observed association between increased BDNF levels and cognitive benefits suggests that acute bouts of exercise may stimulate neurophysiological changes, contributing to improved memory, attention, and executive function (Silakarma et al.,2019). This principle provides a foundational understanding of how exercise can serve as a stimulus for brain health and cognitive performance. (Sudo et al.,2022; Hwang et al.,2016; McIlvain et al.,2024). The research provides evidence for HIIT's significance in cognitive learning, highlighting the more complex character of HIIT regarding neurological activities. Griffin et al.,2011 demonstrated that acute high-intensity cycling exercise was effective in cognitive function by increased concentration of BDNF in young adult males (Griffin et al.,2011). Thus, these studies indicate that the enhancement of cognitive processes may be a factor contributing to athletes' rapid response during high-intensity competitive games. Systematic HIIT exercise also affects cognitive aspects while increasing shortest reaction time, best anticipation, perception, and optimal decision making (Chmura et al.,2023), such an effect is extremely desirable, as it allows players to perform actions efficiently at extremely intense moments of a match.

A recent review summarized that improvements in cognitive performance following high-intensity aerobic exercise are frequently accompanied by the changes in brain activation assessed by Psychomotor task, Executive function, Memory task, Attentional task, Motion Object Tracking Test, and Perceptual Load Test in healthy younger adults, Basketball, and Soccer players. (Herold et al.,2022; Sehrish Shiraz et al.,2024). Despite its established advantages, there is a lack of direct evidence regarding the combined effects of HIIT and SA, particularly focusing on futsal players. Thus, we aimed to evaluate the acute effects of sport-specific high-intensity interval training with step aerobics training (HIITSA) on cognitive in professional futsal players.

MATERIALS AND METHODS

Participants

Fifteen male professional futsal players were randomly allocated to one of two groups: One group engaged in HIITSA, while the other group continued their regular futsal training without HIITSA (CON). The resulting sample included fifteen participants, with 8 participants in the exercise group, and 7 participants in the control group that did not exercise. Both groups maintained their standard futsal training routines throughout the study. An a priori power analysis using statistical software (G*power V 3.1.9.4) was completed to determine an adequate sample size. For this sample, the statistical power was 87% (two tails t-test; effect size moderate and alpha: 5%).

The inclusion criteria in this study were as follows: (1) minimum of one year of active participation in futsal (2) age between 18 and 22 years (2) body mass index between 18.5-22.9 kg/m^2 (4) without any injury, acute illness, unstable hypertension, and angina (5) having regular futsal training sessions for at least three weeks prior to the study. Exclusion criteria included any known exercise-limiting cardiovascular or respiratory condition, lower limb fractures, or musculoskeletal injuries within three months prior to study initiation. All athletes were informed of the risks, benefits, and participation requirements of this study before signing a written informed consent form. This study was approved by the Ethics Committee of Khon Kaen University (approval number HE672108).

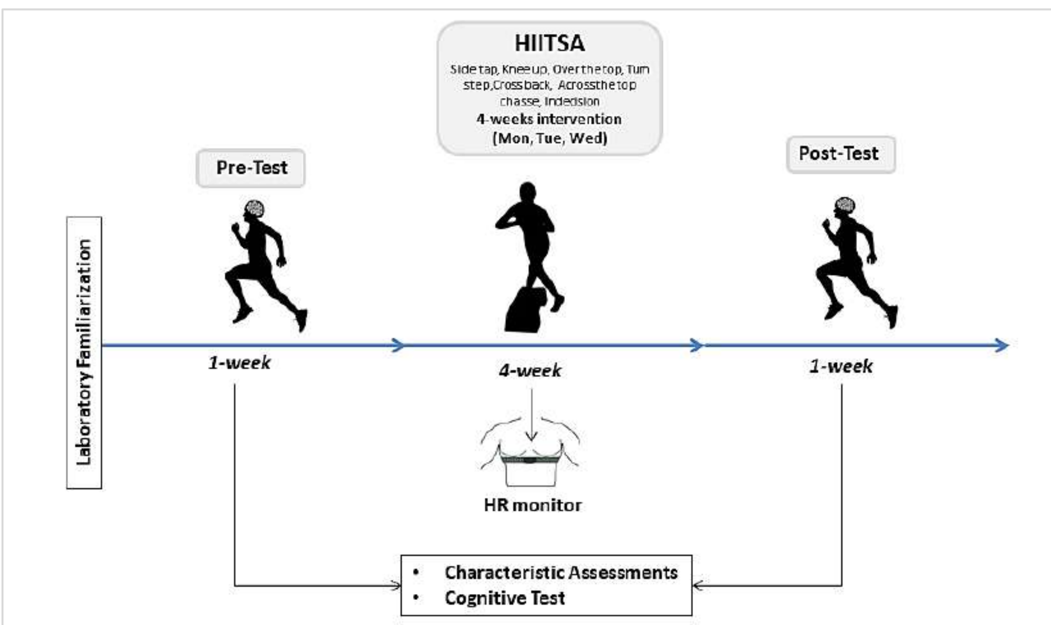


Figure1. Study design.

Experimental approach

A randomized controlled study was designed to investigate the acute effects of sport-specific high-intensity interval training with step aerobics training (HIITSA) on cognitive responses in professional futsal players. All subjects completed a pre-test cognitive test within 1 week before starting the intervention. After the pre-tests, the participants were randomly assigned to either the high-intensity interval training combined with step aerobics protocol (HIITSA), and the control group (CON) for 4 weeks of intervention. Post testing was performed 1 week after the cessation of the intervention (Figure1).

Procedures and measurements

The baseline characteristic assessments, Morphological included body height, body weight, fat mass, fat-free mass, and leg muscle mass was measured using a stadiometer and bioelectrical impedance method (InBody Body Composition Analyzer, Tanita Company). BMI was measured calculated based on body height and weight. Heart rate at rest was recorded in beats per minute (bpm) using the Polar10 (Polar H10 Heart Rate Monitor Chest Strap, Finland), were performed both 1 week before and after the training intervention.

The performance assessments including cognitive performance test the test used was inspired by the work of Sekulic et al.,2019 this study employed a cognitive test (Sekulic et al.,2019), were performed both 1 week before and after the training intervention. Measurements were performed on 3 separate days, with a 48-h interval, following the same order for both pre-tests and post-tests. All subjects were familiarized with the test protocols and experimental devices in advance. The subjects were also instructed to strenuous and prolonged exercise (lasting more than 30 minutes) 24 h before each test day. Testing was started with a warm-up consisting of 10 min of jogging and 10 min of dynamic stretches as directed by the researcher.

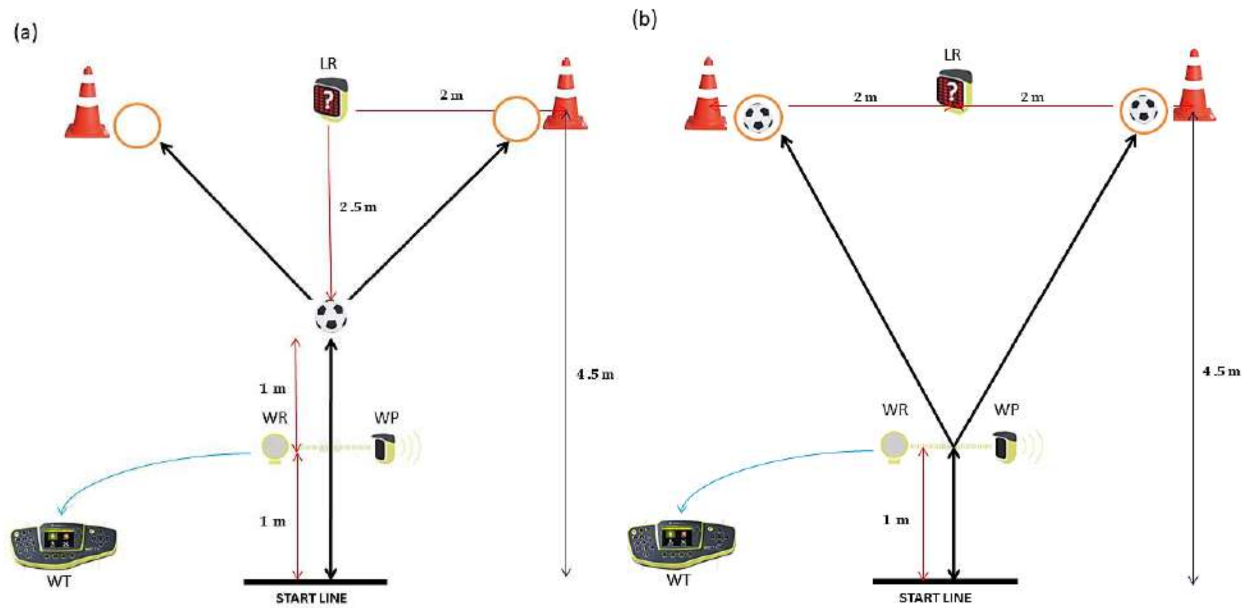
High intensity interval training with step aerobics Intervention (HIITSA)

The HIITSA included multiple functional exercises combination with 6 inch steps aerobics using training moves consisting of seven movement patterns: 1) side tap, 2) knee up, 3) over the top, 4) turn step, 5) cross back, 6) across the top chasse, and 7) indecision. Each exercise was performed to rhythmic music (170 bpm for exercise intervals and 70 bpm during recovery periods) and executed on a 6-inch aerobic step platform (Jansupom et al., 2023). In each HIITSA session, participants were required to wear Polar H10 to record heart rate and track exercise intensity in real-time. The monitor was positioned near the heart and secured with a chest strap, with heart rate data managed through the Polar team system (Polar team system, Finland). The maximum heart rate (HRmax) of each session is considered to be exercise periods by 20 s at 90% HRmax according to the Tabata protocol (Tabata., 2019), interspersed with 10-second recovery periods at 60% HRmax. Each participant's HRmax was determined using the age-predicted formula (220 - age) x percent intensity, with 90% applied to active intervals and 60% during recovery. Participants were provided with qualitative feedback, such as "*you should go faster*" or "*you did a good job*," to aid in perceiving and adjusting to the prescribed intensity levels. Each training session commenced with a standardized warm-up, followed by a 10-minute jog, and concluded with a cool-down phase that also included a 10-minute jog. Heart rate was maintained at 60% of HRmax during both the warm-up and cool-down phases. The exercise program consists of 8 sections, the total HIITSA session duration was 50 minutes.

Cognitive tests

To assess cognitive performance, the test used was inspired by the work of Sekulic et al.,2019 this study employed a cognitive test (Sekulic et al.,2019). The WittySEM photocell system (Microgate S.r.I.Via Waltraud Gebert Deeg, 3eI-39100 Bolzano, ITALY) is used to assess agility in this study (Molinaro et al.,2023), which has one photocell, each with an optical proximity sensor and a 7 × 5 LED matrix that can display different colours, arrows in several directions, numbers, letters, and other symbols.

During each trial, timing for the test commenced when participants departed from the start line 1 m behind the timing gate after seen the signal light from the traffic light of the 7x5 LED matrix display (LR; LED Reaction Smart Indicators) that can display different arrows in several directions and concluded at the first infrared signal (WP; Witty Photocell, WR; Witty Reflector) point (Figure2). For statistical analysis, each variable was tested twice, and the best performance score for each participant from each test by a tablet witty timer via a radio transmission system (Microgate S.r.l.Via Waltraud Gebert Deeg, 3eI-39100 Bolzano, ITALY) was recorded for analysis in real time for the acquisition of events.



Note. WP; Witty Photocell, WR; Witty Reflector, LR; WT; Witty timer via a radio transmission system, LR; LED Reaction Smart Indicators.

Figure 2. Testing of the Cognitive tests by futsal specific change of direction speed and reactive agility including (a) dribbling and (b) ball touching Test.

Statistical analysis

Data analyses were performed with academic statistics software (SPSS, Version 28). Data were reported as mean ± standard deviation (Mean ± SD). Statistical analyses were performed using paired-sample t-tests to compare pre- and post-intervention measurements within each group. Independent-sample t-tests were used to compare differences between groups. The level of statistical significance was set at $p \leq .05$.

RESULTS

Baseline characteristic

No significant differences were found in terms of age, height, body mass, fat mass, fat-free mass, leg muscle mass, or body mass index before and after the intervention period between the two teams (HIITSA and CON) (mean: age = 19.89 ± 0.93 years; height = 170 ± 4.06 cm; body mass = 60.17 ± 3.73 kg; fat mass 13.60 ± 3.47 %; fat free mass 36.96 ± 1.68%; Leg Muscle mass 53.76 ± 1.40%; Body mass index 20.88 ± 1.03 kg/m^2.) (Table 1).

Cognitive performance assessed by cognitive test, decreased after the intervention only in the HIITSA group (RAG_DD (p = .037), RAG_DND (p = .004), RAG_TD (p = .033), RAG_TND (p = .010), CODS_DD (p = .007, p = .001), CODS_DND (p = .009, p = .003), CODS_TD (p = .005), and CODS_TND (p = .050, p = .001)

(Table 2). Also, the post-intervention values were higher in the CON group compared to the HIITSA group (RAG_DND (p = .008), RAG_TD (p = .042), RAG_TND (p = .058), CODS_DND (p = .001), and CODS_TD (p = .045). However, there was no significant effect on RAG_DD (p = .153), CODS_DD (p = .080), CODS_TND (p = .094) (Table 2).

Table1. The demographic and anthropometric data of the futsal players included in two groups.

Variables	**HIITSA(*n* = 8)**		**CON(*n* = 7)**	
	Pre-Test	Post-Test	Pre-Test	Post-Test
Age (years)	19.89 ± 0.93	19.89 ± 0.93	19.78 ± 0.97	19.78 ± 0.97
Height (cm)	170 ± 4.06	170 ± 4.06	172.89 ± 5.57	172.89 ± 5.57
Body mass (kg)	60.17 ± 3.73	60.47 ± 3.53	59.71 ± 6.90	58.90 ± 4.70
Fat mass (%)	13.60 ± 3.47	11.74 ± 3.63	12.44 ± 3.41	11.64 ± 3.02
Fat free mass (%)	36.96 ± 1.68	37.61 ± 1.71	37.55 ± 1.10	37.75 ± 1.15
Leg Muscle mass (%)	53.76 ± 1.40	54.78 ± 1.48	54.52 ± 1.04	54.81 ± 1.12
BMI (kg/m^2)	20.88 ± 1.03	20.92 ± 0.68	19.95 ± 1.55	19.84 ± 1.31

Table 2. Comparison of changes in cognitive performance before and after the high-intensity interval training with step aerobics (HIITSA) of futsal players is presented. Data are shown as means ± standard.

Cognitive Variables		**HIITSA(*n* = 8)**	**CON(*n* = 7)**
RAG_DD (s)	Pre-Test	0.09 ± 0.13	0.84 ± 0.15
	Post-Test	0.82 ± 0.15*	0.90 ± 0.12
RAG_DND (s)	Pre-Test	0.84 ± 0.11	0.87 ± 0.02
	Post-Test	0.86 ± 0.10**	1.00 ± 0.07*
RAG_TD (s)	Pre-Test	0.79 ± 0.10	0.87 ± 0.08
	Post-Test	0.81 ± 0.13**	0.93 ± 0.09*
RAG_TND (s)	Pre-Test	0.80 ± 0.17	0.79 ± 0.15
	Post-Test	0.83 ± 0.06**	0.92 ± 0.10*
CODS_DD (s)	Pre-Test	0.47 ± 0.18	0.58 ± 0.21
	Post-Test	0.66 ± 0.16*	0.80 ± 0.18*
CODS_DND (s)	Pre-Test	0.54 ± 0.22	0.64 ± 0.18
	Post-Test	0.64 ± 0.11**	0.86 ± 0.11*
CODS_TD (s)	Pre-Test	0.63 ± 0.14	0.60 ± 0.07
	Post-Test	0.61 ± 0.16**	0.74 ± 0.07*
CODS_TND (s)	Pre-Test	0.65 ± 0.14	0.58 ± 0.13
	Post-Test	0.55 ± 0.19*	0.68 ± 0.14*

Note. RAG_DD — Reactive agility with dribbling on the dominant side, RAG_DND — Reactive agility with dribbling on the non-dominant side, RAG_TD — Reactive agility with ball touching on the dominant side, RAG_TND — Reactive agility with ball touching on the non-dominant side, CODS_DD — Change-of-direction speed with dribbling on the dominant side, CODS_DND — Change-of-direction speed with dribbling on the non-dominant side, CODS_TD — Change-of-direction speed with ball touching on the dominant side, CODS_TND — Change-of-direction speed with ball touching on the non-dominant side. An asterisk (*) indicates a significant difference from pre-training (p ≤ .05), (**) indicates a significant difference between groups (p ≤ .05).

DISCUSSION

We are aware of very few studies using any type of HIIT exercise with SA that have examined whether over 4-weeks duration of exercise training increases cognitive. Prior to our study, the shortest HIIT study on cognitive performance consisted of only single session of HIIT, with 6 session of sprints, each lasting 6 seconds, with a 60-second rest period between each set (Herold et al.,2022). The main finding was that 4-week of high intensity interval training with step aerobics allowed futsal players significantly improves cognitive function for the HIITSA group, while it remained reduction in the cognitive performance for the CON group.

This our finding accordance with previous studies shown that engagement in even a single session of HIIT exercise can improve cognitive performance in the short term (McIlvain et a.,2024; Herold et al.,2022) and may be explained by the relates to the nature of HIIT and SA, interaction between high-intensity exercise and enhanced cognitive processing (Samuel et al.,2017, Slusher et al.,2018; Solianik et al.,2020). Chmura et al. (2023) report that HIIT protocol intensities closer to psychomotor fatigue threshold (PFT) is significant for cognitive performance ,(Chmura and Nazar., 2010), as exercising at an intensity close to this threshold maximizes CNS efficiency (shortest reaction time, best anticipation, perception, and optimal decision making) and enhances cognitive processes. It also maintains the well-known benefits of high-intensity, repeated efforts (Chmura and Nazar., 2010; Chmura et al.,2023). Additionally, these cognitive gains are consistent with previous research by Shiraz et al. (2024), which elucidated the cognitive benefits of high-intensity interval training (HIIT) among athletes (Shiraz et al.,2024). The improvement in cognitive functions may significantly contribute to enhanced sports performance by enabling more efficient speedier decision-making, more situational awareness, and better focus during competition. Systematic research examine how rhythmic and patterned movements in dance and similar activities, such as step aerobics training also had a substantial positive effect on cognitive functions like spatial awareness and memory (Hewston et al.,2021). One plausible explanation for these outcomes according with further contribute to cognitive improvements by training spatial awareness and working memory as athletes synchronize their movements with complex patterns and rhythms. This enhancement may also be a consequence of the increased coordination required by the body during the rhythmic movements associated with the nature of SA stepping up and down. Consequently, this could be linked to the improved functionality of the brain regions responsible for motor control (Dunsky et al., 2017).

On the contrary, the findings of this study suggest that HIITSA was the absence of significant muscle hypertrophy post-training, likely due to the short duration period, which is consistent with previous research suggesting that HIIT exercise requires 6-12 weeks to observe significant muscle hypertrophy (Caparrós-Manosalva et al.,2023; Longlalerng et al.,2021; Molinari et al.,2022). Importantly, it can be surmised that the cognitive performance enhancements that were observed were likely the result was positively correlated with cognitive responses that were induced following HIITSA training, which was completed in a brief four weeks. Moreover, HIITSA has the potential to directly enhance neural system function, contributing to improved motor control and cognitive processing abilities (Yue L al et.,2023; Dincher et al.,2023, Wu Z J et al.,2021; Shiraz et al.,2024). Previous studies have demonstrated that BDNF is sensitive to exercise, which might lead to improved cognitive performance (Li et al., 2022). Our study was in agreement with the findings of Herold et al. (2022) and Sehrish Shiraz et al. (2024), who have confirmed that HIIT improves cognitive performance following high-intensity aerobic exercise. The mechanisms underlying the effects of HIITSA exercise on cognitive function are well-established. One possible explanation for this finding may be to enhance brain-derived neurotrophic factor (BDNF), which might stimulate synaptic connections and learning and memory, (Fernandez-Rodriguez et al., 2022), ultimately contributing to improvements in memory, attention, and executive function. This is achieved by enhancing the execution of motor skills, maintaining sustained focus, and supporting precise decision-making processes during high-intensity competitive matches. Due to the nature of high-intensity interval training, which involves repeated bouts of intense exercise within a limited timeframe followed by rest periods combined with stepping up and down, turning, dancing, and various other coordinated movements. These dynamic and integrative elements may provide cognitive benefits, making

HIITSA an effective training strategy for improving cognitive performance (Neves et al., 2023; Behrens et al., 2017). Accordance with previous studies have shown that this type of exercise stimulates the release of BDNF (brain-derived neurotrophic factor) in the brain (Li et al.,2023; Fernandez-Rodriguez et al., 2021; Vaynman et al.,2004). This release enhances learning processes, leading to improved brain function, specifically by increasing responsiveness to stimuli, and more efficient information processing (Sehrish Shiraz et al.,2024; Silakarma et al., 2019; Herold et al. (2022).

In futsal the total distance covered during the match consists of 13.7% high intensity running and 8.9% sprinting (Spyrou et al., 2020). Decision-making is a critical factor in determining success in the context of high-intensity games, where rapid responses and constant focus are required. Thus, in these studies indicate that the enhancement of cognitive processes may be a factor contributing to athletes' rapid response during high-intensity competitive in the fast-paced of game. Due to the small field size, this is an inevitable limitation in a dynamic sport that requires athletes to respond quickly. This approach may serve as a strategic advantage in fast sprints, better decision-making in futsal players closer to the characteristics of the sport.

CONCLUSION

In conclusion, the current study demonstrated that a short training period using HIITSA sessions can significantly improve cognition in elite young futsal players. This protocol promoted as a time-efficient alternative to improve cognition (e.g., attention, and decision-making) in a fast-paced match. For future research, it would be important to explore the exact mechanisms behind the increase in BDNF and cognitive improvements, as these may be influenced by factors such as exercise type, intensity, and individual characteristics, and help in developing exercise programs aimed at optimizing cognitive function and brain health in sports.

AUTHOR CONTRIBUTIONS

Study concept and design: N. B. and A. H. Analysis and interpretation of data: A. H., S. P., and C. J. Drafting of the manuscript: N. B. and N. R. Critical revision of the manuscript for important intellectual content: A. H., and T. K. Statistical analysis: A. H. and N. B.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ACKNOWLEDGMENTS

The authors also are highly grateful to the School of Sports Science, Suranaree University of Technology and Rajamangala University of Technology Isan for the help provided during data collection. Special thanks must go to the team manager, head coach, sports scientists, and futsal players of the Northeastern University team for their cooperation throughout this research study.

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ORIGINAL ARTICLE

Attacking players and goal scoring

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ABSTRACT

This paper investigates optimal coaching strategies in the combination of players football managers should have on the field. It does so by examining how goal scoring and conceding respond to changes in the number of attacking players on the field in European football matches. The paper tests the hypotheses that more attacking players raise both the rates at which the team scores and concedes goals. The paper shows that managers play more defenders when their team is an underdog and it tests whether this strategy is successful. The estimates show that teams are nearly always better off including more attacking players on the field. In the typical match, teams score at a greater rate and (surprisingly) concede at a lower rate when they have more attacking players on the field. The gain in net goals from playing more attacking players is larger the more a team is favoured over its opponent. Teams that are heavy underdogs playing away from home are the only ones that may be better off playing more defensive players. Coaching strategies should shift toward being less defensive in most cases.

Keywords: Performance analysis, Home advantage, Managerial decisions, Football, Goal scoring, Sports performance.

Cite this article as:
Magee, C. (2025). Attacking players and goal scoring. *Journal of Human Sport and Exercise, 20*(2), 644-657. https://doi.org/10.55860/tq1a3v39

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Submitted for publication January 24, 2025.
Accepted for publication March 05, 2025.
Published March 26, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/tq1a3v39

INTRODUCTION

Managers of football clubs seek to combine players on the field in a way that will give them the best chance of outscoring their opponents. One common tendency is for teams to play more defensively when they are underdogs or on the road than they do when they are favourites or at home. Are those decisions rational or should managers adopt different strategies? This paper explores optimal coaching strategies by investigating how the combinations of defenders, midfielders, and attackers on the field affect the team's rates of scoring and of conceding goals. The estimates show that in the vast majority of cases, a team has a higher net scoring rate if it has more attacking players on the field. Only heavy underdogs playing away from home do better by adding more defensive players to their lineup on the field. In all other situations, a team that brings attacking players onto the field and removes defensive players increases its rates of scoring relative to that of the opposition.

A natural response to seeing this result might be to wonder if better teams tend to play more attacking players while weaker teams set up more defensively. Thus, teams with more attacking players score more (and are scored on less) because of their quality rather than because of their formation. The empirical model in this paper controls for relative team quality by including a fixed effect for each match. The fixed effects control for the relative strength of the two teams on the day the game is played. In the regressions, the estimation thus captures the difference within the game in scoring between minutes when a team has fewer attacking players on the field and minutes when the team has more attacking players. In all regressions, the score of the game is controlled for to eliminate the possibility that teams try harder to score (and use more attacking players) when they are behind than when they are ahead.

Many studies have examined goal scoring in European football leagues. Rodenas et al. (2020), Pratas et al. (2018), and Sarmento et al. (2014) provide reviews of this literature. Pratas et al. (2018) note that most articles provide only a static analysis that mainly describes key performance indicators rather than examining the dynamics of performance during matches. Sarmento et al. (2014) recommends that researchers incorporate "*situational and interactional contexts into the analysis of football performance*." This paper follows that recommendation.

Several studies examine different methods of attack to see what is most effective. Tenga et al. (2010) compare counter attacks (a more direct style) to elaborate attacks (emphasizing longer spells of possession). They find that counter attacks are more effective than elaborate attacks in home games if the defence is imbalanced or out of its normal shape. This result does not hold in away games, however. Wright et al. (2011) analysed 1788 attempts on goal (of which 167 were scored) in English Premier League games. They find that 85% of goals were scored after a spell of possession less than four passes. Thus, most goals are scored in transition situations.

Coaches and their tactics are the subject of a study by Staufenbiel et al. (2015). Based on survey data, they showed that managers had higher expectations about how they would do and were less satisfied with a 0-0 score when at home than when they were playing an away game. The coaches also tended to choose tactics considered more "*dominant*" and more "*courageous*" when at home. When coaches made a substitution in a tie game in the 70th minute, the home coach substitutions were more offensive than the away coach substitutions. Interestingly, the tactics for all coaches shifted and became more dominant and courageous in the second half than they were at the start of the game. That is consistent with Brocas & Carrillo (2004), who show that coaches adopt a more attacking strategy later in the game if it remains tied.

The increasingly attacking tactics late in the game may help explain a common result in the literature, which is that goal scoring rates tend to rise over the course of the game. Studies finding this result include Ridder, Cramer, & Hopstaken (1994), Dixon and Robinson (1998), Palomino, Rigotti, & Rustichini (1999), Abt, Dickson, & Mummery (2001), Armatas, Yiannakos, & Sileloglou (2007), Alberti et al. (2013), Simiyu (2014), and others. Another potential explanation for rising goal scoring rates as a game nears its end is substitutions, which tend to occur in the later stages of most games. Amez et al. (2021) show that substitutes significantly raise the scoring rates of the substituting team and reduce the scoring rates of the opposing team.

The game score affects scoring rates for both teams. Dixon and Robinson (1998) find that home scoring falls and away scoring rises if the home team is leading. Both teams' scoring rates rise (compared to a tie game) if the away team is in the lead. The difference in goal scoring rates based on game situation may be a result of a change in style of play. Lago (2009) finds that the Espanyol football club in La Liga possessed the ball more while they were losing than they did when they were winning or drawing. Compared to losing positions, possession fell by 3% when the game was tied and fell by 11% when Espanyol was ahead. A similar result emerges in Lago-Peñas and Gómez-López (2014), who found that ball possession decreased when a team was one goal ahead. They show that shots on goal and the probability of reaching the final third of the pitch also fell when a team was one goal ahead.

MATERIAL AND METHODS

This paper uses data from 7,204 matches played in the first divisions of the five largest professional leagues in Europe (England, France, Germany, Italy, and Spain) during the 2017-18, 2018-19, 2019-20, and 2020-21 seasons. The data set includes all of the goals scored in those matches, the timing of each goal, and the players who were on the field in each minute of the game. Each player is identified as either a defender, midfielder, or a forward[1].

The goal of this paper is to identify how the scoring rates of each team are affected by the number of defenders, midfielders, and forwards the two teams have on the field. The first two hypotheses to be tested in the paper relate to how goal scoring and conceding rates are related to the number of attacking players that a team has on the field.

Hypothesis 1: A team with more attacking players on the field will score goals at a faster rate than they would if they had more defensive players.

Hypothesis 2: A team with more attacking players on the field will concede more goals than they would if they had more defensive players.

These hypotheses are intuitive. A team composed primarily of defenders tends to sit deep in its own end, making it hard for the opposition to score but creating few chances of its own to score goals. A team composed of more attacking players will tend to create more scoring opportunities but may be more vulnerable to opposition attacks. Perhaps surprisingly, the estimates in this paper show that only Hypothesis 1 is supported in the data. Hypothesis 2 is rejected emphatically by the empirical tests as the results in the next section show.

[1] *This does not mean that the exact formation being played by the manager can be identified since players are occasionally used in ways that differ from their primary position. What the data can show is how many players of a certain type are on the field at each point in time.*

A third hypothesis examined in this paper, and perhaps one that is less obvious, is that teams with an advantage over their opponents benefit from more attacking lineups while underdogs benefit from including more defenders.

Hypothesis 3: Favoured teams are better off playing more attacking players while underdogs are better off including more defenders on the field.

Based on their home and away lineups, coaches seem to believe Hypothesis 3 to be true. Away managers include significantly more defenders on the field (4.27 on average) than home teams (4.22) while home teams have more forwards (2.22) than away teams (2.15). Using power indexes[2] of each team to measure relative team strength, it is even clearer that managers play more defensive players when they are underdogs. If the home team has a higher power index than the away team, the home team averages 4.16 defenders on the field while the away team averages 4.34 defenders. When the home team has a lower power index, the home team averages 4.28 defenders on the field, significantly more than the away team's 4.20 defenders. Thus, managers send out more defensive players when their teams are at a disadvantage. This paper will assess whether that strategy of playing more defensive players when the opposing team has an advantage makes sense.

To evaluate the hypotheses, the empirical model examines the determinants of goal scoring rates for the home and away team. Each observation is for a single minute in a particular game. There are 648,360 minutes observed across the 7,204 matches played.

The key question of interest is the effect on scoring rates of how attacking the lineup of each team is. To measure the attacking value of the lineup, I assign an attacking value of zero to each defender, one to each midfielder, and two to each forward. The attacking value of the lineup is the sum of these values across all ten field players, and it ranges from three to 14 in the data set. The median value of eight reflects the most common lineup combination in the dataset: four defenders, four midfielders, and two forwards. The regressions include the attacking value of the lineup for the home team and for the away team, as well as the square and the cube of these values. Including the square and the cube of the two attacking value variables allows the lineup attacking values to have nonlinear effects on the scoring rates of the two teams.

Testing Hypothesis 3 requires a model in which the impact of the lineup attacking value on goal scoring rates depends on whether the team is a favourite or an underdog. The models measure the relative strength of the two teams using the difference between the home and away team power indexes. This variable measuring relative team strength is interacted with the attacking values of the home team and the away team lineups.

Other variables related to the game situation can also affect scoring rates and are included in the model as control variables. Because scoring rates rise as the game approaches its end, the model includes the minute of the game and the minute squared. Previous research has found that scoring rates rise faster over the course of the match when there is greater attendance, so the model also includes an interaction term between the log of attendance and the minute variable. The referees add extra time at the end of each half to account for injuries, and all goals scored in stoppage time are recorded as occurring in minute 45 or minute 90. Thus, the model includes dummy variables for minute 45 and for minute 90.

[2] *The power index for each team is FiveThirtyEight's rating of overall team strength ahead of each game, described more fully at https://data.fivethirtyeight.com/#soccer-spi. The power ratings include offensive and defensive ratings for each team based on the market value of the players, and they are adjusted after each match based on the team's performances.*

The game score can influence scoring rates if the team that is behind tries harder to score or gives up trying to score if it is too far behind. Thus, the model includes six dummy variables indicating game score: home team ahead by three or more goals, home ahead by two goals, home ahead by one, and away ahead by one, two, or three or more goals. The omitted category is a tie game. The effects of the game score on scoring may differ, however, depending on whether it is early in the game or late (the urgency to catch up may be greater for the trailing team if it is late in the match, for instance). To account for this possibility, the model includes interaction terms between the minute of the game and each of the game score variables. To allow substitutions to affect scoring, the model includes the number of home team substitutes in the game and the number of away team substitutes in the game. Finally, if a team has gotten a red card, they are forced to play down a player the rest of the match, which affects both teams' scoring, so the numbers of red cards for the home and away teams are also included.

In addition to the control variables listed above, the regressions all include a fixed effect for each match, which controls for any factors specific to the game that affect the outcome. These include attendance, the referee, the relative strength of the teams and their form at the time, the distance the away team had to travel, injuries each team had coming into the game, and other factors even more difficult to measure such as any differences between the matches that were played during the pandemic and those played before it. Any factor that is constant across all the minutes within a particular game will be captured by the match fixed effects. With the fixed effects in the regression, the coefficients on the attack value variables measure how changes in the team's attack value within the match are related to changes in scoring rates within the match.

RESULTS

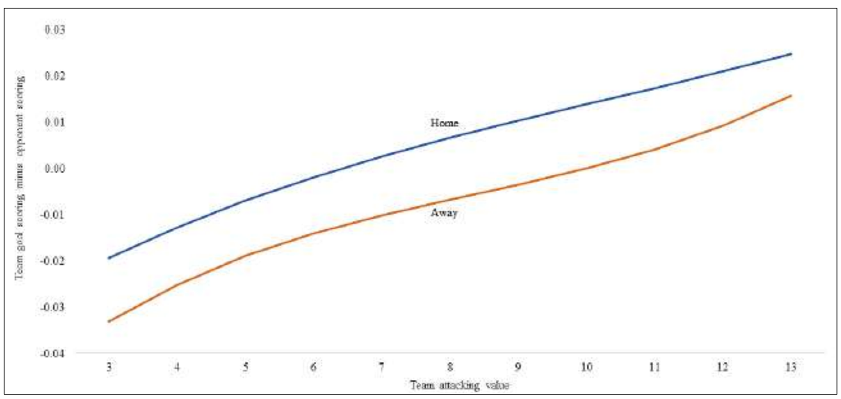
Table 1 presents the results of fixed effect regressions estimating the determinants of goal scoring probabilities per minute. In the first column, the dependent variable is equal to the number of goals scored by the home team in a particular minute of the game. The second column examines scoring by the away team, while column three examines net goal scoring (home goals minus away goals in the minute). The coefficient on each variable in the third column is equal to the coefficient in the first column minus that in the second column.

Table 1. Determinants of goal scoring rates per minute.

Variable	Home goals		Away goals		Net goals	
Minute	0.03925	***	0.02917	***	0.01007	**
Minute squared	-0.02943	***	-0.02051	***	-0.00892	*
Minute*Ln(attend)	0.00058	***	-0.00012		0.0007	***
Minute 45	0.0307	***	0.02518	***	0.00552	
Minute 90	0.07953	***	0.07222	***	0.00731	
Home ahead 3+	-0.10829	***	0.01928	***	-0.12757	***
Home ahead 2	-0.07923	***	0.01008	***	-0.08931	***
Home ahead 1	-0.03974	***	0.00764	***	-0.04739	***
Away ahead 1	0.01022	***	-0.03719	***	0.04741	***
Away ahead 2	0.01359	***	-0.08049	***	0.09409	***
Away ahead 3+	0.01285	**	-0.11818	***	0.13103	***
Home red cards	-0.01214	***	0.01483	***	-0.02696	***
Away red cards	0.01495	***	-0.00663	***	0.02158	***
Home subs	0.0013	***	-0.00048		0.00179	***
Away subs	-0.00113	***	0.00023		-0.00135	***
Attack value home	0.00427		-0.02656		0.03083	

Attack value home squared	-0.00004		0.00131		-0.00134	
Attack value home cubed	-0.0000002		-0.00002		0.00002	
Attack value away	-0.11213	**	-0.04285		-0.06928	
Attack value away squared	0.00609	**	0.0025		0.00359	
Attack value away cubed	-0.00011	**	-0.00005		-0.00007	
Power index diff * home attack	0.00011	***	0.00002		0.00009	**
Power index diff * away attack	0.00012	***	-0.00005	**	0.00017	***
Minute * Home ahead 3+	0.04906	***	-0.01051	*	0.05957	***
Minute * Home ahead 2	0.05165	***	0.00023		0.05142	***
Minute * Home ahead 1	0.02753	***	-0.00051		0.02803	***
Minute * Away ahead 1	-0.00407	*	0.02519	***	-0.02926	***
Minute * Away ahead 2	-0.00154		0.05611	***	-0.05765	***
Minute * Away ahead 3+	0.00009		0.05892	***	-0.05883	***
F-statistic, home attack	19.74	***	3.85	***	18.07	***
F-statistic, away attack	4.86	***	17.26	***	14.96	***
Observations	648.180		648.180		648.180	

*Note. *, **, *** indicate that the coefficient is statistically significant at the 10%, 5%, and 1% levels. Standard errors allow correlation between observations from within the same game. The models include fixed effects for each match.*

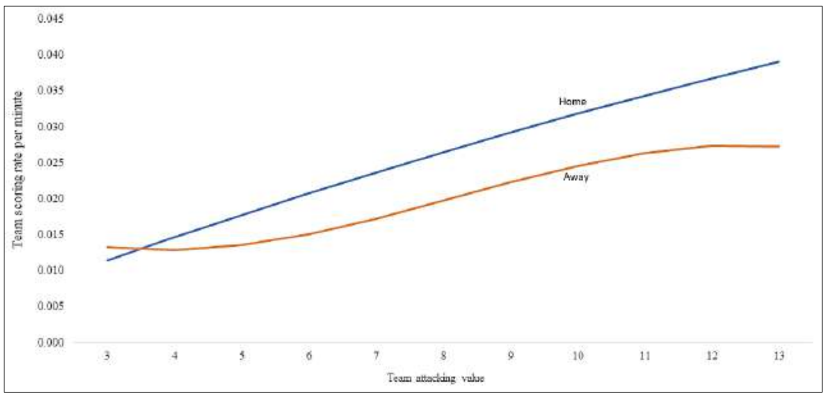


Note. Team attacking value is the stun of attack value for each player on the field where defender = 0, midfielder = 1, forward = 2. The vertical axis shows the probability of the team scoring in the next minute minus the probability of the opposing team scoring in the next minute in a tie game between two evenly matched teams with no red cards and no substitutes. The opposing team's attacking value is set to 8, and the average values are assumed for minutes and attendance. Based on Column 3 from Table 1.

Figure 1. Net goal scoring per minute by team attacking value.

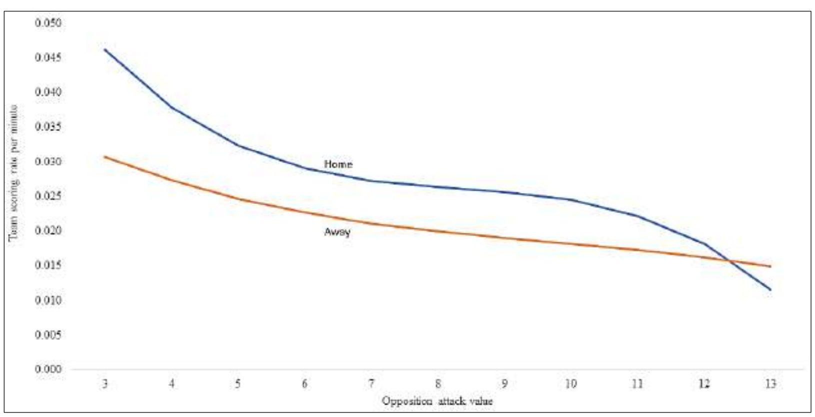
The regressions in Table 1 include variables measuring the attacking value of the home and away lineups, the squares of those values, and the cubes of those values. The F-statistics for the three home team attack value variables and for the three away team attack variables are listed near the bottom of the table. The home attack value variables have a jointly significant impact on both home scoring and away scoring rates, and the same is true for the away team attack variables. The home lineup has a more significant impact on home scoring than on away scoring, while the away lineup has a more significant impact on away scoring. Figure 1 illustrates the effect of the team’s lineup on the net scoring rate (team scoring minus opponent scoring) in the average minute of a tie game between two evenly matched teams. Both home and away teams do very poorly when they have heavily defensive lineups, but each does much better when they introduce more attacking players onto the field. The estimation suggests that teams have better net scoring rates the more attacking their lineups are. In the data there is very little evidence that a lineup can be too attack-oriented if the two teams are even in terms of quality.

How big is the effect on net goal scoring of increasing the number of attacking players on the field? Based on the estimates in column 3 of Table 1, the home team's net scoring (home expected goals minus away expected goals) rises by 0.0037 per minute if it raises the attack value of its lineup from eight to nine while the away team lineup's attacking value remains at eight. That change in net scoring would project to a 0.34 increase in the home team's net goal advantage for the game if it were sustained over 90 minutes. For the away team, raising the attack value of its lineup from eight to nine while holding the home team value constant would improve the away team's net scoring by 0.0032 per minute, or by 0.29 net goals over a full game. These are large effects. In the data set, the home team outscores the away team on average by 0.34 goals per game when there are fans in the stadium. Thus, replacing one defender with a midfielder (or a midfielder with a forward) for all 90 minutes has about the same impact on the game outcome as does having home field advantage.



Note. Team attacking value is the sum of attack value for each player on the field where defender = 0, midfielder = 1, forward = 2. The vertical axis shows the probability of the team scoring in the next minute in a tie game between two evenly matched teams with no red cards and no substitutes. The opposing team's attacking value is set to 8, and the average values are assumed for minutes and attendance. Based on Columns 1 and 2 from Table 1.

Figure 2. Team scoring rates by team attacking value.

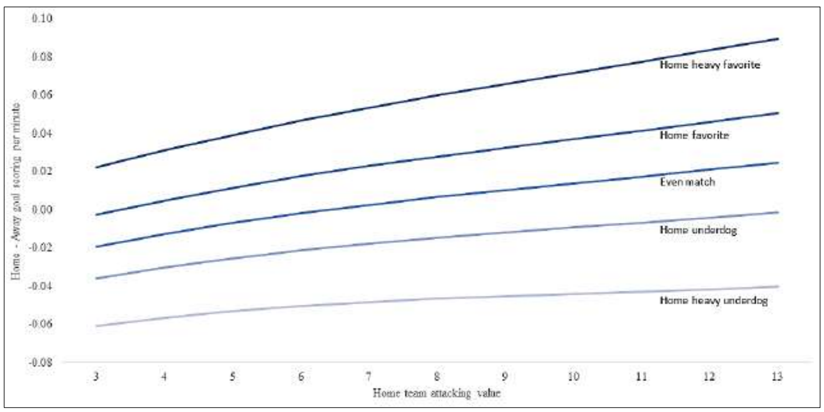


Note. Opposition attacking value is the sum of attack value for each of the opposing team's players on the field where defender = 0, midfielder = 1, forward = 2. The vertical axis shows the probability of the team scoring in the next minute in a tie game between two evenly matched teams with no red cards and no substitutes. The scoring team's attacking value is set to 8, and the average values are assumed for minutes and attendance. Based on Columns 1 and 2 from Table 1.

Figure 3. Team scoring by opposition lineup attacking value.

We can use columns 1 and 2 in Table 1 to determine how the attacking value of a lineup affects the team's own scoring and how it affects the scoring of the opposition. Figure 2 shows how the home and away team lineups affect their own scoring rates per minute. The effect is slightly larger for the home team, but for both home and away teams, having more attacking players on the field means that the team will score at a higher rate.

Figure 3 presents evidence that (in addition to raising the team's own scoring rate) having more attacking players on the field also reduces scoring by the opposition. Again, the effect is larger for the home team, but for both home and away teams, the opposing team scores fewer goals per minute if a team puts more attacking players on the field than if it plays primarily defenders.



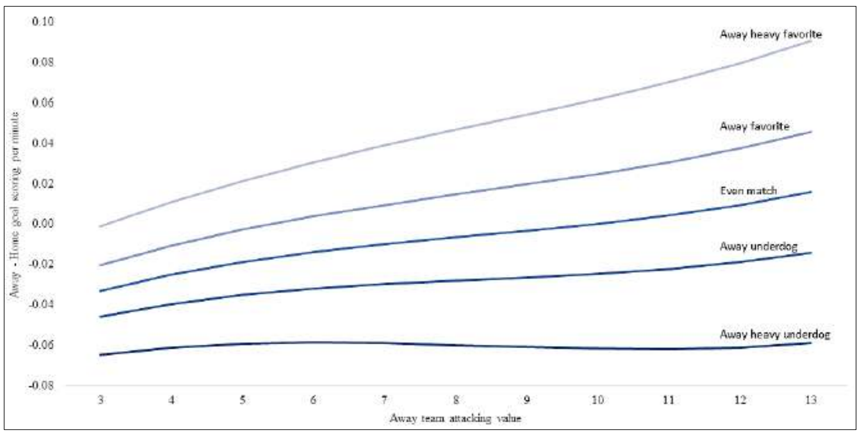
Note. Team attacking value is the sum of attack value for each player on the field where defender = 0, midfielder = 1, forward =2. The figure shows a tie game with no red cards and no substitutes. The opposing team's attacking value is set to 8 (the median), and the average values are assumed for minutes and attendance. Heavy team favourites mean the team is at the 95th percentile in the difference between values for the team power indexes. Favourites mean that the team is at the 75thpercentile in the difference between values for the team power indexes.

Figure 4. Net goals per minute, home attack value, and relative team strength.

The model investigates this possibility by including interaction terms between the attacking values of each team and a measure of their relative strength. The significant positive coefficient on the home attack – power index interaction term in Column 1 means that the more the home team is the favourite, the bigger the positive impact on home scoring an attacking home lineup has. When the home team is an underdog, putting an attacking lineup on the field has a smaller but still positive impact on home scoring. Figure 4 illustrates how home attack values are related to net goal scoring for five different types of matches: the home team as a heavy favourite, home team as a favourite, an even matchup, away team as a favourite, and away team as a heavy favourite. A heavy favourite is the favoured team when the difference between the two teams' power indexes is at the 95th percentile while a favourite indicates that the difference is at the 75th percentile. An underdog or heavy underdog is the weaker team in those games. As the figure shows, even when the home team is a heavy underdog, it still does better when it plays a more attacking lineup, though the advantage of playing an attacking lineup is largest when the home team is a heavy favourite.

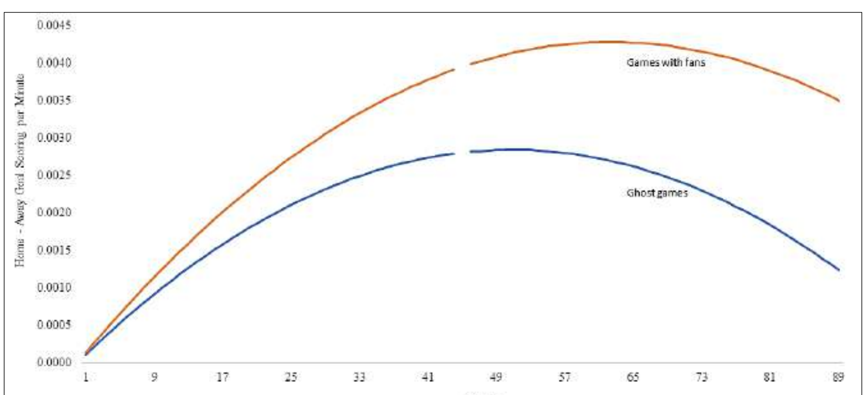
In a game in which the away team is a favourite and both home and away teams have an attacking lineup value of eight, the home team is expected to lose the game by 1.31 goals. If the home team raises the attacking value of its lineup value to nine, it is expected to lose only by 1.06 goals. Thus, raising the attacking value of the lineup leads to an improvement of 0.25 net goals for the home underdog. If the home team is the favourite, however, and it raises the attacking value of its lineup from eight to nine (while the away team remains at eight), the home team's expected winning margin rises from 2.52 goals to 2.94 goals. The gain in expected winning margin from an increase in the home team lineup's attacking value is thus larger when the home team is the favourite (0.42 goals) than when it is the underdog (0.25 goals).

There are also significant coefficients on the power difference – away team attack value interaction terms in both the home and away scoring regressions. The positive coefficient on this interaction term in the home scoring regression means that if the home team is a heavy enough favourite, having more attacking players on the field for the away team can lead to more goals by the home team. The negative coefficient on this interaction term in the away scoring regressions means that when the home team is a heavy favourite, the away team having more attacking players on the field has a smaller positive impact on away scoring. These results suggest that the away team may want to put out a more defensive lineup if it is a heavy enough underdog.



Note. Team attacking value is the sum of attack value for each player on the field where defender = 0, midfielder = 1, forward = 2. The figure shows a tie game with no red cards and no substitutes. The opposing team's attacking value is set to 8, and the average values are assumed for minutes, attendance. Heavy team favourites mean the team is at roughly the 95111 percentiles in the difference between values for the team power indexes. Favourites mean that the team is at roughly the 75111 percentiles in the difference between values for the team power indexes.

Figure 5. Net goals per minute, away attack value, and relative team strength.



Note. Net goal scoring is the probability of the home team scoring in the next minute minus the probability of the away team scoring in the next minute in a tie game with no red cards and no substitutes. Both teams' attacking values are set to 8. Attendance for games with fans is set to the median value for non-ghost games (25,365). Based on column 3 from Table 1.

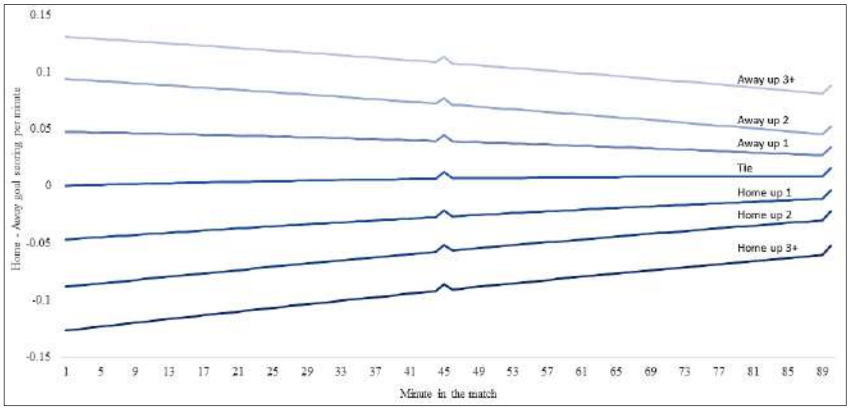
Figure 6. Home — away net goal scoring rate per minute, ghost and fan games.

Figure 5 illustrates the impact of the away team lineup on the away team's net scoring (away goals minus home goals per minute). If the away team is the stronger team, or if it is even close to the home team in quality, the away team should play more attacking players, and the more attacking lineup the better. If the away team is a very heavy underdog, on the other hand, it may be better off sending out a defensive lineup or making defensive substitutions. When the game is at the 95th percentile in terms of the home team's power index advantage over the away team, the away team maximizes its net scoring rate when it has a lineup with an attacking value of six. The most common lineup with this attacking value has five defenders, four midfielders, and one forward.

The results for the control variables are intuitive. As the positive coefficient on minutes and the negative coefficient on minutes squared in the first two columns indicate, both teams' goal scoring rates increase until near the middle of the second half, at which point scoring rates begin to fall. Home goal scoring rises faster over the course of the game if there is a large crowd in the stadium. This result suggests that the size of the crowd has an increasing positive influence on home team scoring as the game approaches its end. The crowd does not significantly affect away scoring rates. Both home and away teams are estimated to be more likely to score in minutes 45 and 90, though the greater stoppage time added at the end of the game means the effect for minute 90 is more than twice as large as the effect for minute 45.

The net goal scoring regression in column 3 shows that in games with many fans in the stadium, the home team has an increasingly large advantage in scoring over the away team as the game progresses. Figure 6 shows the effect of crowds by comparing net goal scoring during each minute of the match during games played during the pandemic when fans were excluded from the stadium (ghost games) to games played with the median attendance level prior to the pandemic. During ghost games, the home team's advantage in scoring rates peaks during minute 51 of the game, at which point the home team is expected to score 0.0028 more goals in a minute than the away team. In the median game with fans, on the other hand, the home team's scoring advantage peaks in minute 62, at which point the home team is expected to score 0.0043 more goals per minute than the away team. The estimates predict that the home team will score 0.19 more goals during the game than the away team if there are no fans in the stadium and 0.29 more goals in a game with the median number of fans. In the average game in the data set, the home team scored 0.34 more goals when there were fans in the stadium. Together, these estimates suggest that about 30% of the scoring advantage received by the home team in a typical game is due to the fans. This estimate falls in between that of two previous studies. Van de Ven (2011) and Ponzo and Scoppa (2018) examined matches between two teams that shared the same stadium but where the designated home team had more fans in the stadium. Van de Ven (2011) concluded that having more fans did not lead to a home advantage in these games. Ponzo and Scoppa (2018), on the other hand, found that the home team retained 60% of the normal home advantage even when the two teams shared the same home stadium, suggesting that most of home advantage is due to crowd support.

Table 1 shows that the score in the match has a large impact on scoring rates, with the team that is behind more likely to score than the team that is ahead (all else equal). Compared to being tied, the home team's expected goal scoring in a minute early in the match falls by 0.04 if it is ahead by 1 goal, falls by 0.08 if it is ahead by two goals, and falls by 0.11 if it is ahead by three goals. Home scoring rises by 0.01, on the other hand, if it is behind. For the away team, scoring early in the match falls by 0.04, 0.08, and 0.12 respectively if it is ahead by one, two, and three or more goals. Away team scoring rises by 0.01, 0.01, or 0.02 if it is behind by one, two, or three or more goals rather than being tied. Interestingly, for both teams there is a much larger drop in scoring when the team takes a lead than there is a rise in scoring when it falls behind.



Note. Net goal scoring is the probability of the home team scoring in the next minute minus the probability of the away team scoring in the next minute. The values are estimated based on column 3 from Table 1 assuming a game with no red cards, no substitutes, and with both teams' attacking values set to 8. Attendance for games with fans is set to the median value for non-ghost games (25,365). Homel, Home2, and Home3 (Away, Away2 and Away3) indicate that the home team (away team) is ahead by 1 goal, two goals, three or more goals respectively.

Figure 7. Net goal scoring rates, game score, and minute.

The effect of the game score on the home team's net advantage in scoring rates depends on the minute of the match. The models include interaction terms between minute and the game score dummy variables, and the coefficients on these interaction terms are significant in Column three at the 1% level, both individually and collectively. Figure 7 shows how the model's predicted net scoring rates during each minute depend on the game score. The game score has a very large impact on scoring rates early in the match, but as the match approaches the end, the effect of the game score diminishes. At all points in the game, the team that is behind has a net scoring advantage over the team that is ahead.

In games that are tied, the home team and the away team begin the game with almost exactly equal chances of scoring in a typical game between equally matched teams. By the end of the game, however, the home team's scoring advantage is considerable. If the home team's scoring advantage in minute one was maintained over the full 90 minutes, the home team would win on average by 0.02 goals. The home team's scoring advantage in minute 89, if extended over the full game, would mean a home win of 0.74 goals.

Column one in Table 1 shows that each extra substitution made by the home team significantly raises home scoring rates while away team substitutions reduce home scoring. Neither home nor away substitutions significantly affect scoring by the away team, as column two shows, though the signs of the coefficients are consistent with a rise in away scoring when the away team makes substitutions and a fall in away scoring with home team substitutions[3].

Column three shows that home substitutions have a significant positive impact on the home team's net scoring rate while away team substitutions significantly reduce the home team's scoring advantage. The result that home scoring rises with home team substitutions and falls with away team scoring is similar to the conclusion of Amez et al (2021), who found that substitutions reduce scoring by the opposing team and the first two substitutions raise the team's own scoring. Unlike this paper, however, Amez et al. (2021) also found that away team scoring rises with the first two away substitutions and falls with all home substitutions.

[3]*Later substitutions do not have a significantly different impact on scoring rates than earlier substitutions do in the data set.*

DISCUSSION

The results described above provide clear evidence on each of the three hypotheses tested in this paper. As Figure 2 shows, there is strong evidence in support of Hypothesis 1. Having more attacking players on the field means that the team will score at a higher rate. While this result is hardly surprising, it supports what coaches expect about their substitutions. In the survey by Wittkugel (2022), 93% of coaches responded that bringing on more attacking players would result in a higher scoring probability.

The more interesting results relate to Hypothesis 2, that the likelihood of conceding a goal would be higher with more attacking players on the field. Professional coaches have somewhat mixed views on this question. In the survey by Wittkugel (2022), only 41% of managers responded that an offensive substitution would increase the chance of conceding but 71% of managers felt that a defensive substitution would reduce the chance of conceding. The estimates strongly refute the idea that bringing on more attacking players and substituting out defensive players will increase a team's rate of conceding goals. As Figure 3 shows, when the two teams on the field are relatively equal, having more attacking players on the field actually reduces scoring by the opposition. The strategy of "*parking the bus*," or playing many defensive players to stop the other team from scoring, is not only not successful but is actively harmful. Teams are more successful at preventing the other team from scoring during the minutes that they have more attacking players on the field than they are during minutes when they primarily have defenders on the field. One potential explanation could be that attacking players force the opposing team to keep their players in more defensive positions on the field, which reduces their goal scoring. Another explanation might be that teams with more attacking players can control the ball better than teams that are playing more defenders. Managers in recent years have begun increasingly prioritizing possession of the ball, not only because it raises the chance of scoring, but also because it reduces the chance of conceding. The estimates in this paper show that playing an attacking lineup can be an effective way of defending, either through ball possession or by posing a threat to the opponent's goal.

With more attacking players raising the probability of scoring and reducing the probability of conceding, teams clearly have better net scoring rates with more attacking players in evenly matched games. Perhaps, however, the advantages of attacking players are asymmetrical, and weaker teams should be more defensive in their lineups, as Hypothesis 3 proposes. Managers seem to believe this hypothesis, as they play more defensive lineups on average when they are the underdogs. The estimates in this paper provide evidence that stronger teams get a larger benefit from including attacking players than weaker teams do. Even the weaker team in a matchup, however, is better off playing more attacking players in the vast majority of situations. The estimates from Table 1 show that the away team's net scoring improves if it changes its lineup to become slightly more attacking in over 91% of the minutes played between 2017 and 2021. The away team is better off making substitutions to become more defensive in only 9% of the minutes. Magee (2025) shows that managers become more defensive in their substitutions when they are playing an away game in a stadium with a large crowd. The estimates in this paper suggest that shifting the lineup to be more defensive is a mistake over 90% of the time.

How should we evaluate Hypothesis 3, then? It is true, consistent with the hypothesis, that teams who are favourites get more of an advantage (than underdogs do) from playing an attacking lineup. Even underdogs, however, benefit from playing a more attacking lineup in the vast majority of cases. Only away teams who are far inferior to their opponents should consider shifting their lineups to be more defensive. Hypothesis 3 would thus be a more accurate reflection of reality in professional football leagues if it was revised to say that favoured teams are better off playing more attacking players while heavy underdogs away from home are occasionally better off playing more defenders.

CONCLUSIONS

This paper estimates how the number of attacking players on the field affects scoring rates for teams in the top five European football leagues. The paper evaluates three hypotheses. Not surprisingly, there is strong evidence in favour of the hypothesis that having more attacking players on the field increases the likelihood that a team scores a goal. Perhaps somewhat surprisingly, however, teams also concede fewer goals in the vast majority of matches if they have a more attacking lineup. Thus, teams almost always do better when they shift their lineups to become more attacking. The only exception to this conclusion is for teams that are playing away from home and that are at a huge disadvantage relative to their opponent in terms of team quality. In those cases, a relatively defensive lineup of five defenders, four midfielders, and one forward minimizes the expected loss in the match. Such cases are rare, however. Based on the estimates in this paper, the away manager is better off replacing a defensive player with a more attacking one over 91% of the time.

Are managers being overly defensive in their lineups, then? The estimates in this paper suggest that they have been. It would not be the first time that conservative decisions by coaches reduced their team's chances of winning. Analytics long suggested that coaches in American football should go for it on fourth down much more often than they did in games. Yam and Lopez (2019) estimate that a better fourth down strategy would have gained teams an average of 0.4 extra wins per year in the National Football League between 2004 and 2016. Only in the last few years have coaches in American football shifted their decision making to be more attack-minded on fourth downs. This paper argues that a similar revolution toward attacking play should happen among managers in European football leagues.

SUPPORTING AGENCIES

No funding agencies were reported by the author.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author.

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ORIGINAL ARTICLE

The acute effect of blood flow restriction or ischemia on countermovement jump performance

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ABSTRACT

The aim of this study was to evaluate the effect of blood flow restriction (BFR) or ischemia (IS) used between countermovement jumps (CMJ) on power performance changes. Two groups of participants implemented two separate experimental protocols: BFR as protocol no. 1 and IS as protocol no. 2. Protocol no. 1 involved seventeens male (n = 14) and female (n = 3). Protocol no. 2 involved twenty-three active male (n = 15) and female (n = 8). During each experimental session, following a randomized crossover design, the subjects performed 4 sets of 2 repetitions of CMJ with a 7-minute rest interval. In protocol no.1, the subjects during the rest interval used the appropriate: BFR 60%AOP or 80%AOP or control condition. In protocol no.2 subjects during the rest interval used appropriate: IS 100%AOP or control condition. The two-way repeated measures ANOVA for protocol no.1 as well for protocol no.2 did not show statistically significant condition × set interaction for average force, average power, relative peak power, relative peak force and jump height. There was also no main effect of conditions for both protocols. The results of this study indicates that neither BFR nor IS, regardless of cuff pressure, do not led to improvements in jump performance.
Keywords: Sport medicine, Cuff, Occlusion, Jumping, Power performance.

Cite this article as:
Bichowska-Pawęska, M., Fostiak, K., Gawel, D., Trybulski, R., Alexe, D. I., Szura, E., & Wilk, M. (2025). The acute effect of blood flow restriction or ischemia on countermovement jump performance. *Journal of Human Sport and Exercise, 20*(2), 658-670. https://doi.org/10.55860/1wmw9h79

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Submitted for publication November 28, 2024.
Accepted for publication January 10, 2025.
Published March 26, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/1wmw9h79

INTRODUCTION

Ischemia (IS) as well as blood flow restriction (BFR) are noteworthy training methods drawing significant research interest. Both of these concepts refer to controlled restriction of blood flow, however they differ in regard to the degree of closure of the blood flow. BFR refers to application of cuffs which cause compression in order to reduce the arterial blood flow, while during IS the arterial blood flow is fully blocked. The level of compression is commonly determined as % of arterial occlusion pressure (AOP) which is the individualized value of pressure at which the blood flow to a limb is ceased (the value of 100% AOP determine complete blockage of blood flow to a limb; Patterson et al., 2019). There are five primary BFR or IS methods, i.e.: pre-conditioning (used only before the exercise; Salagas et al. 2022), post-conditioning (used after the completion of the exercise; Daab et al., 2020), continuous (applied continuously during sets and rest intervals; Volga Fernandes et al., 2022; Wilk et al., 2020), intermittent (applied only during the exercise; Wilk et al., 2020) and intra-conditioning (used during only the rest intervals; Fostiak et al., 2022, Bichowska-Pawęska et al., 2024; Gawel et al., 2024).

Ischemic intra-conditioning stands out as a novel and relatively uncomplicated approach to the BFR method. The use of intra-conditioning BFR/IS method preserves the integrity of the movement structures during the exercise because the cuffs are applied only during rest intervals. Furthermore, this method reduces subjective rates of pain and discomfort (Fitschen et al., 2014), contrary to other methods of applying BFR (Schwiete et al., 2021). There is only study that has examined the effects of intra-conditioning BFR/IS in regards to acute changes in power output and bar velocity, however the research outcomes are contradictory (Wilk et al., 2021; Jarosz et al., 2021; Trybulski et al., 2023; Gawel et al., 2024). The differences in obtained study protocols may be explained by the variety of the BFR/IS variables such as the compression pressure, the duration of BFR/IS or the duration of reperfusion (Gawel et al., 2024).

The duration of BFR or IS in intra-conditioning lasted usually from 3 to 6.5 minutes, causing different acute responses (Jarosz et al., 2021; Salagas et al., 2022; Fostiak et al., 2022; Pugh et al., 2024; Bichowska-Pawęska et al., 2024; Gawel et al., 2024). The latest research indicates that also the duration of reperfusion may have a significant impact on acute metabolic responses (Trybulski et al., 2022; Gawel et al., 2024). Further exercise and particular variables (number of sets, repetitions, exercise type, limb circumference, sex, blood pressure) may be of importance as well (Loenneke et al., 2014; Vehrs et al., 2023; Montoye et al. 2023). Therefore, the assessment of the effect of BFR/IS requires taking into account both BFR, training and particular variables.

Currently scientific data suggests that intra-conditioning BFR may allow to increase acute power performance during resistance exercise performed with upper (Wilk et al., 2021) as well as lower limbs (Trybulski et al., 2022). Even a single cycle of IS (5-minute duration; 100% AOP; 60% 1RM; 5 sets; 3 repetitions) significantly increased bar velocity during the bench press exercise (Salagas et al., 2022). Interestingly, in case of progressive fatigue, the use of BFR allows for limiting the decrease in power output in subsequent sets of squats (Trybulski et al., 2022), but such an effect occurs after at least three BFR cycles. Therefore, the number of ischemia cycles also may be a factor influencing the efficiency of the intra-conditioning method (Bichowska-Pawęska et al., 2024; Salagas et al., 2022). Although, the studies regarding intra-conditioning BFR/IS are contradictory, even if some researches did not show positive changes, no study has demonstrated a decrease in performance justifying the continued research in this regard. Pugh et al. (2024) showed greater physiological stress resulting from ischemic conditioning, what enhanced adaptive mechanisms, improving performance and endurance in high-intensity sports. Therefore, applying ischemic intra-conditioning during rest periods may help sustain high levels of power by mitigating exercise-induced fatigue.

Power output of lower limbs which is often developed through resistance training (Cormie et al., 2007) has been shown to be of great significance for athletes. It is often necessary to generate maximal power output, especially in non-cyclical motions such as throws, leaps, kicks or jumps (Bayrakdaroglu et al., 2022). As generating high levels of power output seems crucial for athletic performance (Jandacka et al., 2011), intra-conditioning BFR/IS may serve as a potential tool to further enhance those adaptive changes, particularly among elite athletes (Wilk/Bogdanis et al, 2021; Salagas et al., 2022). Considering that the acute responses during resistance training with BFR may be dependent on the value of cuffs pressure (reference), we hypothesized that BFR (60% and 80%AOP) or IS (100%AOP) intra-conditioning applied between successive Countermovement Jumps (CMJ) improves the variables determining jump performance.

MATERIALS AND METHODS

Study design

The study was conducted according to a randomized crossover design in which two different groups of participants underwent separate experimental protocols, one with blood flow restriction (P-no. 1), and the second with ischemia (P-no. 2). Each protocol was preceded by a familiarization session conducted one week before the main measurements. In both protocols, the participants performed 4 sets of 2 repetitions of the CMJ with a 7-minute rest interval. In each experimental protocol, the effects of BFR or IS applied only during the rest intervals between sets were assessed. Experimental protocol no. 1 included 3 conditions: BFR60%AOP, BFR80%AOP or a control condition and involved the use of cuffs before the first and between each set of CMJs. Experimental protocol no. 2 included 2 conditions, i.e. 100%AOP and a control condition and involved the use of cuffs before the first, 2nd and 4th set of the CMJ. All testing sessions were performed in the Physical Effort Laboratory at the University of Physical Education and Sport in Gdansk, Poland.

Participants

Experimental protocol no. 1 - BFR

Experimental protocol no. 1 involved 17 volunteers and consisted of 14 males and 3 females (age = 22.18 ± 2.01 years; body mass = 80.44 ± 9.43 kg; height = 181.06 ± 6.49 cm; 100%AOP = 192.94 ± 12.22 mmHg; 80%AOP = 154.35 ± 9.78 mmHg 60%AOP = 115.76 ± 7.33 mmHg).

Experimental protocol no. 2 – IS

Experimental protocol no. 2 involved 23 active volunteers and consisted of 15 males and 8 females (age = 23.48 ± 5.07 years; body mass = 75.83 ± 17.59 kg; height = 177.87 ± 9.41 cm; 100%AOP = 199.14 ± 18.86 mmHg).

The inclusion criteria for both groups were: no cardiovascular diseases (including atrial fibrillation, hypertension, thrombosis, heart failure) and no musculoskeletal injuries 6 months prior to the start of the study (personal declaration). The subjects did not change their basic diet, also they did not use any additional supplements or drugs throughout the duration of the study. Before the beginning of the experimental sessions, the subjects were informed and were aware of the potential risks of participating in the research and they signed a written informed consent. The study was approved by the Bioethics Committee at the University of Physical Education and Sport in Gdansk, Poland (no 3, 13.03.2024), in accordance with the ethical standards of the Declaration of Helsinki, 1983. No participants withdrew from the study.

Procedures

Familiarization session

One week before the main experiment began, the participants from both groups performed a familiarization session. During the familiarization session, the subjects from both groups performed the same warm-up which included jogging (5-min) and dynamic exercises (10-min) such as the gluteal stretch walk (10 repetitions (reps)), quadriceps grab walk (10 reps), bouncing on the spot (double leg) (28 reps), gluteal run (14 reps per leg), walking lunges (6 reps) and CMJ (4 reps) (O'Grady et al., 2021). Then, the participants performed 4 sets of 2 repetition of the CMJ with BFR (60% AOP) applied before the first and between each set of the CMJ.

Experimental session

One week before the start of each experimental protocols, participants from both groups completed a familiarization session. During each familiarization session, subjects from both groups performed 4 sets of 2 repetitions of the CMJ with a 7-minute rest interval, while BFR/IS were applied for 5 minutes, with additional ~60 s for cuff inflation and ~60 s for deflation. Experimental protocol no. 1 involved the use of BFR before the first and between each set of the CMJ with cuff pressure set to 60% or 80%AOP. Experimental protocol no. 2 involved the use of IS before the 1st, 2nd and 4th set of CMJ with cuff pressure set to 100%AOP. The warm-up before each main experimental protocol was the same as that performed in the familiarization session. To assess jumping variables, we used a 75 cm x 75 cm Kistler (Germany) tensometric platform. Participants performed a dynamic CMJ and to isolate leg performance during the CMJ jump, the upper limbs were stabilized at the hip.

BFR/ischemic intra-conditioning procedure

For the BFR and IS, pressure cuffs were applied bilaterally, as high as possible to the femoral groin area. The experiment utilized Fit Cuffs (Fit Cuffs, Denmark) with a 10 cm width. To determine each participant's AOP, after the completion of the warm-up and a 5-minute rest interval a handheld Doppler was used (Edan SD3, Sonoline C doppler with 8 MHz probe, Contec, China).

Participants remained seated during the measurement, and the probe was positioned over the posterior tibial artery to identify the blood pressure at which the auscultator pulse ceased. This procedure, as detailed in previous research (Wilk DOI 626915, Trybulski 2023?), was conducted twice for each limb to ensure accuracy. During the BFR protocol, cuff pressure was set to 60% and 80%AOP AOP (115.76 ± 7.33 mm Hg; 154.35 ± 9.78 Hg, respectively) whereas for the IS protocol cuff pressure was set to 100% AOP (199.14 ± 18.86 mmHg). During both protocols BFR/ischemia were applied for 5 minutes, with additional 60s for cuff inflation and 60 s for deflation.

Statistical analysis

All statistical analyses were performed using Statistica 9.1. Results are presented as means and standard deviations. The Shapiro-Wilk as well as the Levene and Mauchly's tests were used in order to verify the normality, homogeneity and sphericity of the sample data variances. respectively. Differences between the conditions for experimental protocol no.1 were examined using two-way repeated measures ANOVA [3 conditions (BFR 60% AOP vs. BFR 80% vs. control) × 4 sets of CMJ].

For experimental protocol no. 2 the differences between the conditions were examined using two-way repeated measures ANOVA [2 conditions (IS 100% vs. control) × 4 sets of CMJ]. Effect sizes (ES) for main effects and interactions in both protocols were determined by partial eta squared ($\eta 2$). Partial eta squared values were classified as small (0.01–0.059), moderate (0.06–0.137) and large (>0.137). Post hoc comparisons using Tukey's test were conducted to locate the differences between mean values when the main effect or an interaction was found. For pairwise comparisons. ESs were determined by Cohen's d which was characterized as large (d > 0.8), moderate (d between 0.8 and 0.5), small (d between 0.49 and 0.20) and trivial (d < 0.2). Percent changes with 95% confidence intervals (95CI) were also calculated. Statistical significance was set at $p < .05$.

RESULTS

Experimental protocol no. 1

The two-way repeated measures ANOVA [3 conditions (BFR at 60% AOP vs. BFR at 80% vs. control) × 4 sets of CMJ] for average force [N], average power [W], relative peak power [W/kg], relative peak force [N/kg] and jump height [m] did not show a statistically significant condition × set interaction (conditions × sets; $p = .21$; $\eta^2 = 0.08$; $p = .39$; $\eta^2 = 0.06$; $p = .81$; $\eta^2 = 0.03$; $p = .52$; $\eta^2 = 0.05$; $p = .91$; $\eta^2 = 0.02$. respectively; tables 1-5). There was also no main effect of conditions ($p = .67$; $\eta^2 = 0.02$; $p = .38$; $\eta^2 = 0.05$; $p = .11$; $\eta^2 = 0.13$; $p = .76$; $\eta^2 = 0.02$; $p = .21$; $\eta^2 = 0.09$, respectively; tables 1-5).

Table 1. Average force [N] during countermovement jumps under three experimental conditions (experimental protocol no. 1).

Condition	CMJ set 1	CMJ set 2	CMJ set 3	CMJ set 4	*p*-value for interaction	*p*-value for main effect of condition
	[N] (95%CI)	[N] (95%CI)	[N] (95%CI)	[N] (95%CI)		
Control	1532 ± 262 (1398 to 1667)	1511 ± 270 (1373 to 1650)	1524 ± 272 (1384 to 1664)	1500 ± 266 (1363 to 1637)	.21	.67
BFR 60%AOP	1519 ± 274 (1377 to 1660)	1510 ± 264 (1375 to 1646)	1509 ± 263 (1374 to 1644)	1484 ± 255 (1353 to 1615)		
BFR 80%AOP	1506 ± 263 (1371 to 1641)	1522 ± 279 (1379 to 1666)	1494 ± 268 (1356 to 1632)	1496 ± 269 (1358 to 1635)		
ES Cohen's						
CON vs. BFR 60%AOP	0.05	0.00	0.06	0.06		
CON vs. BFR 80%AOP	0.10	0.04	0.11	0.01		
BFR 60%AOP vs. BFR 80%AOP	0.05	0.04	0.06	0.05		

Note. All data are presented as mean with standard deviation [SD]; CI = confidence interval; BFR = blood flow restriction; CMJ = Countermovement Jump; AOP = arterial occlusion pressure; CON = control condition; N = newton.

Table 2. Average power [W] during countermovement jumps under three experimental conditions (experimental protocol no. 1).

Condition	CMJ set 1	CMJ set 2	CMJ set 3	CMJ set 4	*p*-value for interaction	*p*-value for main effect of condition
	[W] (95%CI)	[W] (95%CI)	[W] (95%CI)	[W] (95%CI)		
CON	2199 ± 505 (1939 to 2458)	2134 ± 539 (1857 to 2411)	2156 ± 523 (1887 to 2425)	2130 ± 546 (1849 to 2411)	.39	.38
BFR 60%AOP	2176 ± 521 (1908 to 2444)	2152 ± 522 (1884 to 2421)	2130 ± 503 (1871 to 2389)	2070 ± 477 (1825 to 2315)		
BFR 80%AOP	2117 ± 504 (1857 to 2376)	2130 ± 523 (1861 to 2399)	2094 ± 535 (1819 to 2369)	2074 ± 518 (1808 to 2340)		
ES Cohen's						
CON vs. BFR 60%AOP	0.04	0.03	0.05	0.12		
CON vs. BFR 80%AOP	0.16	0.01	0.12	0.11		
BFR 60%AOP vs. BFR 80%AOP	0.12	0.04	0.07	0.01		

Note. All data are presented as mean with standard deviation [SD]; CI = confidence interval; BFR = blood flow restriction; CMJ = Countermovement Jump; AOP = arterial occlusion pressure; CON = control condition; W = watt.

Table 3. Relative peak power [W] during countermovement jumps under three experimental conditions (experimental protocol no. 1).

Condition	CMJ set 1 [W/kg] (95%CI)	CMJ set 2 [W/kg] (95%CI)	CMJ set 3 [W/kg] (95%CI)	CMJ set 4 [W/kg] (95%CI)	CMJ set 5 [W/kg] (95%CI)	*p*-value for interaction	*p*-value for main effect of condition
CON	50.2 ± 8.3 (46.0 to 54.5)	48.9 ± 8.3 (44.6 to 53.2)	48.5 ± 7.9 (44.4 to 52.5)	48.5 ±9 .6 (43.5 to 53.4)	47.7 ±7.8 (43.7 to 51.7)	.81	.11
60%AOP	49.9 ± 9.0 (45.2 to 54.5)	48.6 ± 8.6 (44.2 to 53.0)	47.9 ± 8.0 (43.8 to 52.0)	46.8 ± 7.8 (42.8 to 50.7)	47.2 ± 7.3 (43.4 to 50.9)		
80%AOP	48.8 ± 8.0 (44.7 to 52.9)	48.2 ± 7.8 (44.2 to 52.2)	47.3 ± 8.3 (43.0 to 51.5)	46.9 ± 7.9 (42.9 to 51.0)	46.9 ± 8.0 (42.8 to 51.0)		
ES Cohen's							
CON vs. 60%AOP	0.03	0.04	0.08	0.19	0.07		
CON vs. 80%AOP	0.17	0.09	0.15	0.18	0.10		
60%AOP vs. 80%AOP	0.13	0.05	0.07	0.01	0.04		

Note. All data are presented as mean with standard deviation [SD]; CI = confidence interval; BFR = blood flow restriction; CMJ = Countermovement Jump; AOP = arterial occlusion pressure; CON = control condition; W = watt.

Table 4. Relative peak force [N/kg] during countermovement jumps under three experimental conditions (experimental protocol no. 1).

Condition	CMJ set 1 [N/kg] (95%CI)	CMJ set 2 [N/kg] (95%CI)	CMJ set 3 [N/kg] (95%CI)	CMJ set 4 [N/kg] (95%CI)	*p*-value for interaction	*p*-value for main effect of condition
CON	231 ± 23 (219 to 243)	226 ± 26 (213 to 239)	229 ± 20 (216 to 242)	227 ± 20 (214 to 240)	.52	.76
BFR 60%AOP	230 ± 24 (217 to 242)	227 ± 21 (216 to 238)	228 ± 22 (217 to 240)	225 ±21 (215 to 236)		
BFR 80%AOP	226 ± 23 (214 to 238)	228 ± 24 (215 to 240)	225 ± 20 (211 to 239)	226 ± 26 (212 to 239)		
ES Cohen's						
CON vs. BFR 60%AOP	0.04	0.04	0.05	0.10		
CON vs. BFR 80%AOP	0.22	0.08	0.20	0.04		
BFR 60%AOP vs. BFR 80%AOP	0.17	0.04	0.14	0.04		

Note. All data are presented as mean with standard deviation [SD]; CI = confidence interval; BFR = blood flow restriction; CMJ = Countermovement Jump; AOP = arterial occlusion pressure; CON = control condition; N = newton; kg = kilograms.

Table 5. Jump height [m] during countermovement jumps under three experimental conditions (experimental protocol no. 1).

Condition	CMJ set 1 [m] (95%CI)	CMJ set 2 [m] (95%CI)	CMJ set 3 [m] (95%CI)	CMJ set 4 [m] (95%CI)	*p*-value for interaction	*p*-value for main effect of condition
CON	0.34 ± 0.07 (0.18 to 0.45)	0.33 ± 0.07 (0.15 to 0.44)	0.33 ± 0.07 (0.17 to 0.46)	0.32 ± 0.07 (0.16 to 0.43)	.91	.21
BFR 60%AOP	0.33 ± 0.07 (0.16 to 0.42)	0.32 ± 0.07 (0.16 to 0.41)	0.32 ± 0.07 (0.15 to 0.42)	0.31 ± 0.07 (0.15 to 0.41)		
BFR 80%AOP	0.32 ± 0.07 (0.18 to 0.45)	0.32 ± 0.07 (0.17 to 0.46)	0.32 ± 0.08 (0.16 to 0.46)	0.32 ± 0.07 (0.16 to 0.43)		
ES Cohen's						
CON vs. 60%AOP	0.14	0.14	0.14	0.14		
CON vs. 80%AOP	0.29	0.14	0.14	0.00		
60%AOP vs. 80%AOP	0.14	0.00	0.00	0.14		

Note. All data are presented as mean with standard deviation [SD]; CI = confidence interval; BFR = blood flow restriction; CMJ = Countermovement Jump; AOP = arterial occlusion pressure; CON = control condition; m = meters.

Experimental protocol no. 2

The two-way repeated measures ANOVA [2 conditions (ischemia 100% AOP vs. control) × 4 sets of CMJ] for average force [N], average power [W], relative peak power [W/kg], relative peak force [N/kg] and jump height [m] did not show statistically significant condition × set interaction (conditions × sets; p = .94; η^2 = 0.01; p = .30; η^2 = 0.05; p = .41; η^2 = 0.04; p = .97; η^2 = 0.01; p = .35; η^2 = 0.04. respectively; tables 6-10). There was also no main effect of conditions (p = .07; η^2 = 0.13; p = .06; η^2 = 0.14; p = .22; η^2 = 0.06; p = .28; η^2 = 0.05; p = .42; η^2 = 0.02, respectively; tables 6-10).

Table 6. Average force [N] during countermovement jumps under two experimental conditions (experimental protocol no.2).

Condition	**CMJ set 1** [N] (95%CI)	**CMJ set 2** [N] (95%CI)	**CMJ set 3** [N] (95%CI)	**CMJ set 4** [N] (95%CI)	***p*-value for interaction**	***p*-value for main effect of condition**
CON	1498 ± 369 (960 to 2155)	1461 ± 371 (957 to 2161)	1446 ± 360 (935 to 2193)	1446 ± 379 (958 to 2288)	.94	.07
IS 100%AOP	1468 ± 387 (885 to 2350)	1438 ± 390 (901 to 2350)	1422 ± 367 (922 to 2065)	1411 ± 363 (918 to 2113)		
ES Cohen's						
CON vs. IS 100%AOP	0.08	0.06	0.07	0.10		

Note. All data are presented as mean with standard deviation [SD]; CI = confidence interval; IS = ischemia; CMJ = Countermovement Jump; AOP = arterial occlusion pressure; CON = control condition; N = newton.

Table 7. Average power [W] during countermovement jumps under two experimental conditions (experimental protocol no.2).

Condition	**CMJ set 1** [W] (95%CI)	**CMJ set 2** [W] (95%CI)	**CMJ set 3** [W] (95%CI)	**CMJ set 4** [W] (95%CI)	***p*-value for interaction**	***p*-value for main effect of condition**
CON	2124 ± 651 (1207 to 3135)	2040 ± 648 (1186 to 3010)	2016 ± 626 (1174 to 2948)	2031 ± 671 (1150 to 3156)	.30	.06
IS 100%AOP	2030 ± 625 (1153 to 2824)	1973 ± 632 (1162 to 2820)	1983 ± 654 (1059 to 3034)	1980 ± 656 (1047 to 2931)		
ES Cohen's						
CON vs. IS 100%AOP	0.15	0.10	0.05	0.08		

Note. All data are presented as mean with standard deviation [SD]; CI = confidence interval; IS = ischemia; CMJ = Countermovement Jump; AOP = arterial occlusion pressure; CON = control condition; W = watt.

Table 8. Relative peak power [W/kg] during countermovement jumps under two experimental conditions (experimental protocol no.2).

Condition	**CMJ set 1** [W/kg] (95%CI)	**CMJ set 2** [W/kg] (95%CI)	**CMJ set 3** [W/kg] (95%CI)	**CMJ set 4** [W/kg] (95%CI)	***p*-value for interaction**	***p*-value for main effect of condition**
CON	50.0 ± 8.5 (35.3 to 65.0)	48.4 ± 7.9 (34.0 to 61.0)	47.3 ± 8.1 (32.8 to 59.8)	47.5 ± 7.8 (32.4 to 59.4)	.41	.22
IS 100%AOP	48.8 ± 8.2 (33.7 to 61.7)	48.3 ± 8.5 (32.6 to 61.6)	47.1 ± 8.7 (29.7 to 58.9)	47.2 ± 8.8 (32.8 to 61.7)		
ES Cohen's						
CON vs. IS 100%AOP	0.14	0.01	0.02	0.04		

Note. All data are presented as mean with standard deviation [SD]; CI = confidence interval; IS = ischemia; CMJ = Countermovement Jump; AOP = arterial occlusion pressure; CON = control condition; W = watt; kg = kilograms.

Table 9. Relative peak force [N/kg] during countermovement jumps under two experimental conditions (experimental protocol no.2).

Condition	**CMJ set 1** [N/kg] (95%CI)	**CMJ set 2** [N/kg] (95%CI)	**CMJ set 3** [N/kg] (95%CI)	**CMJ set 4** [N/kg] (95%CI)	***p*-value for interaction**	***p*-value for main effect of condition**
CON	245 ± 33 (194 to 337)	241 ± 29 (187 to 295)	238 ± 28 (191 to 297)	239 ± 28 (189 to 296)	.97	.28
IS 100%AOP	241 ± 27 (201 to 296)	238 ± 31 (193 to 312)	236 ± 32 (192 to 308)	235 ± 32 (184 to 310)		
ES Cohen's						
CON vs. IS 100%AOP	0.13	0.10	0.07	0.13		

Note. All data are presented as mean with standard deviation [SD]; CI = confidence interval; IS = ischemia; CMJ = Countermovement Jump; AOP = arterial occlusion pressure; CON = control condition; N = newton; kg = kilograms.

Table 10. Jump height [m] during countermovement jumps under two experimental conditions (experimental protocol no.2).

Condition	**CMJ set 1** [m] (95%CI)	**CMJ set 2** [m] (95%CI)	**CMJ set 3** [m] (95%CI)	**CMJ set 4** [m] (95%CI)	***p*-value for interaction**	***p*-value for main effect of condition**
CON	0.32 ± 0.08 (0.21 to 0.45)	0.32 ± 0.08 (0.20 to 0.45)	0.31 ± 0.08 (0.20 to 0.44)	0.32 ± 0.08 (0.20 to 0.43)	.35	.42
IS 100%AOP	0.32 ± 0.08 (0.21 to 0.48)	0.32 ± 0.08 (0.20 to 0.47)	0.31 ± 0.08 (0.17 to 0.43)	0.31 ± 0.08 (0.20 to 0.45)		
ES Cohen's						
CON vs. IS 100%AOP	0.00	0.00	0.00	0.13		

Note. All data are presented as mean with standard deviation [SD]; CI = confidence interval; IS = ischemia; CMJ = Countermovement Jump; AOP = arterial occlusion pressure; CON = control condition; m = meters.

DISCUSSION

The main finding of this study was that intra-conditioning BFR as well as intra-conditioning IS did not increase variables related to jump performance, i.e.: average force, average power, relative peak power, relative peak force and jump height. The lack of significant differences occurred across each compression pressures 60% AOP; 80%; 100% AOP. Therefore, it may be concluded that regardless of the cuff pressure, as well as the number of ischemia cycles the intra-conditioning BFR or IS did not influence acute jump performance, which is in contrast to our hypothesis. Although, the obtained results indicate no increases in jump performance, however it must be emphasized that also no decrease in jump performance was recorded in successive sets of the CMJ.

To the best of the authors knowledge, the present study is the first to evaluate the effects of BFR/IS used during rest periods on CMJ performance which limits the possibility of comparison with other studies. To date, the application of intra-conditioning BFR and/or IS was primarily used during resistance exercise (Teixeira et al., 2018; Torma et al. 2021; Jarosz et al., 2021; Wilk et al. 2021). Previous research has indicated that BFR used between sets of resistance exercises may be a significant factor leading to acute power performance changes (Wilk et al., 2021; Trybulski et al., 2022). For instance, Wilk et al. (Wilk et al., 2021) reported significant increases in power output and bar velocity when intra-conditioning BFR was used during the bench press exercise (5 minutes duration; 80%AOP; 60% 1RM; 5 sets; 3 repetitions). Likewise, Salagas et al. (2022) showed an increase in mean and peak bar velocity when a single cycle of IS was applied before the bench press exercise (5-min duration; 100%AOP; 60% 1RM). Therefore, 5-minutes of BFR or IS in the above-mentioned studies was suitable to induce positive changes, but when the same procedure was performed between the CMJs such a positive effect was not observed. It is worth considering the importance of external loading when intra-conditioning BFR. Most studies that showed a positive effect of intra-conditioning BFR used external loading. However, studies using a protocol without external loading did not show such changes (Fostiak et al., 2022). For example, in Wilk et al. (2021) and Salagas et al. (2022) studies, a load of 60% of 1RM was used. On the contrary, a study analysing the intra-conditioning BFR (5-min duration; 60% and 80% AOP) during a running protocol (without external load) did not show any changes in performance (Fostiak et al., 2022) what is similar to the results of our study. Taking this into consideration, it might be concluded that changes in the results after BFR or IS intra-conditioning occurred when high muscle tension was observed caused by external load. Conversely, in the absence of an external load stimulus, no such changes were observed.

Attention should also be paid to the direction of the intra-conditioning BFR effect. Some studies show an increase in power output following intra-conditioning BFR, while others studies show a beneficial effect on decreasing power output loss during multiple sets of resistance exercise. Trybulski et al. (2022), on the contrary to other studies did not find any increases of performance following intra-conditioning BFR, however reported significantly lower decline in power output during the squat exercise. Perhaps, for BFR or IS to be effective, it likely requires effort that generates fatigue, which did not occur during the CMJ. In our protocol of CMJ tests the extended rest periods (7 minutes) allowed for full recovery. The possible influence of IS/BFR on the development may be further supported by the lack of decline in CMJ performance across subsequent sets also under control conditions. Furthermore, recent studies have shown that body position significantly affects the baseline measurement of 100%AOP (Queiros et al., 2024). Higher mean AOP occurs in measurements taken in the standing position compared to the supine and sitting position. Therefore, in order to standardize BFR pressure, Queiros et al. (2024) suggest that baseline measurement of 100%AOP should be performed in the same body position in which the effort will be executed. In the conducted studies, the AOP measurement was performed in the sitting position and the exercise in the standing position, which could have a significant impact on the actual cuff pressure. However, it should be emphasized that none of the cuff pressures applied in our protocol did not show significant changes in CMJ test results.

Another factor that should be taken into account is the area in which the cuffs are applied. All previous studies that have shown improved power output following intra-conditioning BFR have involved the use of a protocol that included upper body exercise. However, the acute effect of BFR may vary between the upper and lower limbs (Trybulski et al., 2022; Trybulski et al., 2023). For example, Gepfert et al. (2020) showed that to induce positive changes after ischemia, the lower limbs require a significantly higher pressure value (150% AOP) compared to the upper limbs. Also, a recent study by Queiros et al. (2024) demonstrated significant differences in AOP measurements between the lower and upper extremities. The authors have shown that the lower limbs require higher cuff pressure to achieve the same degree of BFR compared to the upper limbs. Additionally, as Enko et al. (2011) points out, as the application of BFR cycles increases, the blood vessels progressively widen, attaining their peak diameter after the third cycle. Hence, it appears advisable to incorporate more than one BFR cycle within an intra-conditioning method of training. Thus, based on previous research, it can be concluded that the number of cycles of BFR and IS (5 and 4 respectively) used in our study was sufficient to have a positive effect on jumping variables. However, the results of this study do not confirm these expectations, even though different cuff pressures were used in both protocols (60%, 80%, 100%AOP).

To fully appreciate the scope and implications of the study, it is crucial to consider its primary limitations, which may influence the observed outcomes. Above all, this is the first study to examine the effect of BFR and IS intra-conditioning on jump performance, which is limited by the lack of generalizability or comparison of results across different research protocols. Moreover, while intra-conditioning IS positively impacted power performance when 100% of AOP was used (Pugh et al., 2024), our study shows no significant improvements (60%, 80%, 100%AOP) in body-weight movement such as jumping, suggesting that factors other than % of arterial occlusion pressure may determine the effectiveness of this method. As Spitz et al. (2020) points out, varying body positions, such as seated, supine, and standing can lead to significant differences in the pressure required to achieve effective arterial occlusion, as each position alters blood flow dynamics and limb positioning. In our study, AOP was measured in a seated position with extended legs, which does not reflect the standing position used during jump exercises, therefore composing the main limitation of our study. This variability underscores the importance of aligning the AOP measurement position with that used in the exercise to ensure consistency and accuracy (de Queiros et al., 2024) when BFR/IS method was used. In addition, BFR applied during physical exercise causes a higher level of motor unit activity (Yasuda et al., 2013), increased cell swelling (Loenneke et al., 2012), as well as increased muscle protein synthesis (Fujita et al., 2007) and satellite cell proliferation (Nielsen et al., 2012) compared to exercise without BFR. BFR has been shown to positively impact post-exercise growth hormone concentration (Takarada et al., 2000; Suga et al., 2009) and insulin-like growth factor IGF-1 compared to control conditions (Takano et al., 2005). Thus, despite no improvement in jump performance in our study following the BFR/IS intervention, we may assume that such a training intervention may have a beneficial effect on acute metabolic and hormonal responses. However, in the present study, the physiological and metabolic responses were not determined on an acute basis. Thus, future research should explore the above mentioned factors and their linkage in order to better understand the conditions under which intra-conditioning BFR and IS might enhance athletic performance, particularly in dynamic, lower-limb exercise.

CONCLUSIONS

The results of this study demonstrate that neither BFR nor IS, regardless of cuff pressure (60%, 80%, 100%AOP), led to improvements in jump performance variables such as average force, average power, relative peak power, relative peak force and jump height. The absence of performance enhancement in this study suggests that the effects of BFR and IS may be exercise-specific and more pronounced in contexts involving mechanical overload, such as resistance training, rather than dynamic, unloaded movements like jumping. However, despite the lack of performance gains, BFR/IS intra-conditioning effectively maintained jump performance levels without the progressive decline typically seen over successive sets. This maintenance of performance may facilitate chronic muscle adaptations while minimizing acute performance trade-offs. Thus, future research should focus on examining the underlying physiological mechanisms and testing alternative protocols, including body position during AOP measurements and external load incorporation, to clarify the potential of BFR and IS in enhancing performance in dynamic lower-limb activities.

AUTHOR CONTRIBUTIONS

Study design, MB-P. Data collection, MB-P, KF, ES and RT. Statistical analysis, MB-P and MW. Data interpretation, MB-P and MW. Manuscript preparation, MB-P, DG, RT and MW. Literature search, MB-P, DG, DIA. All authors have read and agreed to the published version of the manuscript.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Impact of apnoea training on metabolic and cardiovascular health in sedentary adults

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ABSTRACT

Apnoea, an underwater practice that involves the voluntary suspension of breathing, has gained popularity among high-performance athletes and individuals seeking to improve their physical health. We sought to evaluate the effects of a 16-week apnoea training program on body composition and metabolic and cardiovascular biomarkers in university teachers. A pretest-post-test quasi-experimental design was used in a group of nine university teachers. The program included five progressive stages of apnoea training. Measurements were taken before and after the intervention, following the WHO STEPS Surveillance Protocol, evaluating anthropometric, cardiovascular, and metabolic variables. Data were analysed using normality and t-student tests for paired samples. It was found that, although there were no significant changes in participants' body composition, substantial reductions in fasting glucose, total cholesterol, NHDL-C, and haematocrit levels were observed after the intervention. These results suggest improvements in glycaemic regulation and lipid profile, contributing to a reduction in cardiovascular risk. These findings underscore the potential of apnoea as an intervention to improve metabolic and cardiovascular health in sedentary populations.
Keywords: Sport medicine, Apnoea, Cardiovascular risk, Metabolic health, Body composition, Physical training.

Cite this article as:
Jiménez Trujillo, O. H., Gaviria Chavarro, J., Collazos Otero, A., Facundo Duarte, A., & Rojas-Padilla, I. C. (2025). Impact of apnea training on metabolic and cardiovascular health in sedentary adults. *Journal of Human Sport and Exercise, 20*(2), 671-681. https://doi.org/10.55860/26c4z227

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Submitted for publication February 03, 2025.
Accepted for publication March 11, 2025.
Published March 26, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/26c4z227

INTRODUCTION

Apnoea is a sport that consists of voluntary suspension of breathing in the water while traveling long distances or descending into it, it is an extreme sport that has begun to gain strength among non-athletes to improve their physical condition or state of health. Despite its growing popularity, few studies evaluate its impact on metabolic and cardiovascular health in untrained populations such as university teachers, who according to other authors, may constitute a group susceptible to developing chronic diseases associated with physical inactivity, sedentary lifestyles, and other lifestyle-related risk factors (Peinado et al., 2017) such as cardiovascular risk (Rojas-Padilla et al. 2022).

Apnoea training induces significant physiological adaptations such as improved oxygen storage capacity and its optimization in muscles (Lamaitre et al., 2015), increased ability to tolerate hypoxia along with better heart rate control (Perini et al.2008), and modulation of the sympathetic nervous system response, contributing to the reduction of resting heart rate (Lugo et al.,2023). These cardiovascular and metabolic changes contribute to maintaining an adequate state of health.

In terms of metabolism, apnoea has been linked to improvements in blood glucose regulation, a crucial aspect for the prevention and control of metabolic diseases such as type 2 diabetes mellitus, since exposure to hypoxia during apnoea can activate metabolic pathways that improve insulin sensitivity and favour glucose utilization by muscles (Andersson & Schagatay, 2008). This suggests that apnoea could be used as a tool not only to improve athletic performance but also to control metabolic risk factors and improve health status in susceptible populations.

On the other hand, the impact of apnoea on the lipid profile has been the subject of research, with results indicating a possible improvement in cholesterol and triglyceride levels, as well as a reduction in the risk of atherosclerosis (Svedenhag & Linnarsson, 1986) because apnoea training can reduce low-density lipoprotein (LDL) levels and increase high-density lipoprotein (HDL), which is a positive marker for cardiovascular health. Complementary to the above, it is necessary to identify additional parameters with utility as predictors of cardiovascular disease, among them: plasma atherogenic index (AI) (Tamarit, 2022), atherogenic coefficient (AC), remnant cholesterol (RC), non-high-density cholesterol (NHDL-C) and atherogenic index of plasma (AIP), which are better predictors of cardiovascular risk (Cao et al., 2020; Varbo et al., 2013).

Most studies on the effects of apnoea have focused on sports populations or highly trained individuals, leaving a gap in understanding how this type of training might impact less physically active populations, such as university faculty. Thus, it is crucial to investigate how they could benefit from apnoea training, given the potential impact on the prevention of metabolic and cardiovascular diseases, in addition to conferring benefits on body composition (Rezaeipour et al., 2021) representing a significant and positive contribution to global public health (Peinado et al., 2017).

The present study aimed to identify the effects of a 16-week apnoea training program on fasting glucose, body composition, anthropometric measures, cardiovascular variables and metabolic biomarkers in a population of university teachers.

METHODS

Study design

This study used a pretest-post-test quasi-experimental design to evaluate the effects of an apnoea training program on body composition, anthropometric variables, and metabolic and cardiovascular biomarkers in a group of university teachers. The study design allowed the observation of changes in the variables of interest before and after the intervention.

Context
The study was conducted in Santiago de Cali, Colombia, which is 995 meters above sea level, at a university institution from August to November 2023. The apnoea training program took place in a semi-Olympic pool and was conducted by a PADI Diving Instructor.

Participants
The sample consisted of nine female university teachers with an average age of 39 years, an average weight of 73.4 kg, and an average height of 1.69 meters. The participants were selected considering inclusion and exclusion criteria.

Inclusion criteria
Women of legal age, linked to the apnoea training program of the university institution; with minimum attendance of 90% to the training sessions and who had submitted signed informed consent and the medical examination report.

Exclusion criteria
Participating in sports training other than apnoea, having a diagnosis of cardiovascular or metabolic diseases, presenting morpho-functional alterations that would limit the training process, missing training sessions or voluntarily withdrawing from the study at any program stage.

Sample size
The sample size was limited to nine participants. Although this number is small, it is adequate to explore initial trends and the feasibility of the apnoea training program in this specific population. Future research with larger sample sizes will be necessary to validate the findings of this study.

Table 1. Operational definition of some variables that make up the physical condition associated with health.

Categories	Variables	Operational definition	Reference values	Measurement Units	Instruments
Body composition	Abdominal circumference	Anthropometric measurement to determine the level of cardiovascular risk in an individual.	≥ 80 M y ≥ 90 H	cm	Lufkin metal tape measure
	% Body fat	Bioelectrical impedance technique used to measure body composition based on the body's ability to conduct an electrical current.	> 33,9	%	Electronic scale (OMRON)
	% Muscular Mass		> 24,1		
	Body Mass Index	Body Mass Index is an index of the relationship between weight and height, generally used to classify underweight, overweight and obesity in adults.	≥ 25	kg/m^2	
Cardiovascular	Systolic blood pressure	When the heart is at rest between beats resulting in a decrease in blood pressure	≥ 130	mmHg	Sphygmomanometer consisting of sphygmomanometer, cuff and stethoscope.
	Diastolic blood pressure	Force exerted by the blood against the walls of the arteries. Each time the heart pumps blood into the arteries	≥ 85		
	Resting Heart Rate	Resting heart rate		Lat/min	
	Peripheral oxygen saturation	Amount of oxygen (in percent) bound to haemoglobin in red blood cells	98%	%	Pulse oximeter
Blood biochemistry	Total cholesterol	Metabolite levels measured in blood by dry chemical methods.	≥ 190	mg/dL	vitros 5,1 FS
	cHDL		40 - 50		
	cLDL		≥ 130		
	Glucose		≥ 100		
	Incremental Remaining Cholesterol I	Factors that are considered for cardiovascular disease according to serum lipoprotein levels	> 4.5	-	Formulas
	Incremental Remaining Cholesterol II		> 3.0		
	Plasma atherogenic index		> 0,24		
	Atherogenic coefficient		> 2.8		
	Haematocrit	Ratio of red blood cells	40 - 45 %	%	vitros 5,1 FS

Variables
Anthropometric variables: weight, height, abdominal perimeter, and body mass index (BMI).

Body composition variables: percentage of body fat, percentage of muscle mass, and visceral fat index.

Cardiovascular variables: systolic blood pressure (SBP) and diastolic blood pressure (DBP), resting heart rate (RHR), resting peripheral oxygen saturation (SpO_2), total cholesterol (TC), high-density lipoproteins (HDL), low-density lipoproteins (LDL), atherogenic coefficient (AC), plasma atherogenic index (AIP), remnant cholesterol (CRI), non-HDL cholesterol (NHDL-C) and haematocrit.

Metabolic variable: Fasting glucose.

Aerobic fitness variable: swimming meters using the Cooper 12-minute test.

Data source

Data were collected at two key moments: baseline measurements (pre-intervention) and final measurements (post-intervention). Measurements of cardiovascular, metabolic, anthropometric, and body composition variables were performed following the WHO STEPS Surveillance Protocol, which guarantees the standardization of procedures, and the reliability of the data obtained. Anthropometric variables were evaluated by an ISAK level II certified anthropometrist; muscle mass and body fat measurements were measured with bioimpedance, cardiovascular data, and medical examination were performed at the physical fitness centre of the University Institution and laboratory analysis at a clinical laboratory authorized by the municipal health secretariat (authorization code #7600107211).

Bias

The study implemented several strategies to minimize bias, including standardization of measurement techniques and constant monitoring of training sessions. However, the lack of a control group is a limitation that may introduce bias in the interpretation of the effects of the intervention. In addition, the small sample size may limit the generalizability of the results.

Training

The training was developed in five stages, each designed to progressively increase the intensity and complexity of apnoea training (Table 2).

Table 2. Training description.

Week	Activity	Exercise	Distance (meters)
Week 1 to 3 100% Surface	Warm up	Freestyle swimming	200
	Swimming	Freestyle swimming-breaststroke	600
	Cool-down	Freestyle swimming	200
	Total distance stage		**1000**
Week 4 to 5 80% Surface 20% apnoea	Warm up	Freestyle swimming	400
	Swimming with mask and snorkel		200
	Basic apnoea equipment		200
	Dynamic apnoea 12.5 m	Free kick / dolphin	100
	Dynamic apnoea 20 m		100
	Surface recovery between each dive	Static and dynamic	100
	Cool-down	Freestyle swimming	400
	Total distance stage		**1500**
Week 6 to 8 60% Surface 40% apnoea	Warm up	Freestyle swimming	400
	Basic freediving equipment		300
	Dynamic apnoea - 25 mt	Free kick / dolphin	100
	Dynamic apnoea - Diagonal pool 30 mt.		240
	Dynamic apnoea - 25 mt		100
	Surface recovery between each dive	Static and dynamic	260
	Cool-down	Freestyle swimming	400
	Total distance stage		**1800**

Week 9 to 13 60% Surface 40% apnoea	Warm up	Freestyle swimming	400
	Basic apnoea equipment		200
	Surface hypercapnic apnoea	Crawl. Progressive stroke cycle	300
	Static apnoea. Progressive times	Pool edge-.50 until 120 seg	0
	Hypoxic dynamic apnoea - 20 mt	Free kick / dolphin	100
	Dynamic apnoea - 30 mt		120
	Dynamic apnoea - 40 mt		120
	Surface recovery between each dive	Static and dynamic	160
	Cool-down	Freestyle swimming	200
	Total distance stage		**1600**
Week 14 to 16 50% Surface 50% apnoea	Warm up	Freestyle swimming	400
	Basic freediving equipment		200
	Dynamic apnoea - 20 mt	Free kick / dolphin	100
	Dynamic apnoea - 30 mt		150
	Dynamic apnoea - 40 mt		200
	Static apnoea. Progressive times	Pool edge- 60 until 120 seconds	0
	Dynamic apnoea - 50 mt	Free kick / dolphin	200
	Dynamic apnoea - 75 mt		150
	Surface recovery between each dive	1 minute static	0
	Cool-down	freestyle swimming	200
	Total distance stage		**1600**

*Note. *Dynamic* apnoea *were performed at a depth of approximately 5.5 meters. After each dynamic apnoea, a static or dynamic pause, or a mixture of both, was performed as a strategy to recover oxygenation and ventilation.*

Data analysis
Data analysis was performed using the R Studio program. Univariate analyses were performed to describe the quantitative variables, calculating the mean and standard deviation. The Shapiro-Wilk test was used to verify compliance with the normality criterion for the variables. Subsequently, a test of equality of variances was performed, followed by the t-student test for paired samples, to compare means before and after the intervention. In addition, 95% confidence intervals were calculated for the mean differences, providing an estimate of the range of possible values for the observed differences.

Statement of ethical issues
This study was done considering the Helsinki Declaration and the Resolution 3480 of Health and Social Protection Minister in Colombia. This research was approved by the code 17.133 of the National School of Sports ethics committee in May 2022. Participation was voluntary and accepted by signing an informed consent. The confidentiality was ensuring through file encryption and use of numerical codes.

RESULTS

The participants in this research were nine female university teachers with an average age of 39 years, who did not perform any type of physical exercise other than apnoea, and who lived in Cali, Colombia.

Several variables related to body composition and anthropometry were evaluated, including abdominal perimeter, weight, body fat percentage, muscle mass percentage, visceral fat index, and body mass index (BMI). All these variables, except weight, showed a normal distribution and homogeneity of variances. However, when applying the t-Student test for paired samples, none of these variables showed significant differences between pre-and post-intervention measurements (Table 3).

Table 4 shows the pre-and post-intervention results of the variables evaluated in plasma; among these, only Non-High-Density Lipoprotein Cholesterol (NHDL-C) showed a significant decrease after the intervention (*p*-value = .036), with a reduction in the mean from 160.4 to 146.8 mg/dL. The other atherogenic indices, such as HR-I, HR-II, AIP, and AC, showed no statistically significant changes, indicating that these parameters remained stable throughout the study. Similarly, this table shows the pre-and post-intervention results of the hemodynamic variables and the physical swimming test; within these findings, only diastolic blood pressure presented a significant difference (*p*-value = .003462), reducing from 72.78 mmHg to 64.17 mmHg after the intervention. As for the physical swimming test, although an improvement was observed in the distance swum (from 459.2 m to 491.1 m), this difference did not reach statistical significance (*p*-value = .1028).

Table 3. Body composition variables.

Variables	**Media**	**Standard Deviation**	**T test (*p*-value)**
Abdominal Perimeter (I)	86.22	9.72	.2002
Abdominal Perimeter (II)	85.2	9.86	
Weight kg(I)	73.36	11.7	.7085
Weight kg (II)	73.03	11.56	
% body fat(I)	29.7	7.35	.5499
% body fat (II)	29.47	7.77	
% muscular mass (I)	32.31	5.78	.4379
% muscular mass (II)	32.51	5.99	
Visceral fat index (I)	8.89	3.69	.6811
Visceral fat index (II)	8.78	3.63	
Body mass index (I)	26.19	3.59	.668
Body mass index (II)	26.06	3.34	

*Note. *(I)pre-intervention evaluation; (II)post-intervention evaluation.*

Table 4. Hemodynamic, plasma, and aerobic fitness variables.

Variables	**Media**	**Standard Deviation**	**T test (*p*-value)**
CRI-I (I)	4.644	1.649	.678
CRI – I (II)	4.525	2.09	
CRI-II (I)	2.999	1.143	.682
CRI-II (II)	2.907	1.54	
AIP (I)	0.1551	0.2512	.443
AIP (II)	0.1059	0.312	
AC (I)	3.644	1.649	.678
AC (II)	3.525	2.09	
(NHDL-C (I)	160.4	33.03	.036
(NHDL-C (II)	146.8	44.41	
SpO_2(I)	96	1.06	.8487
SpO_2 (II)	95.94	1.1	
FCR(I)	64.56	10.31	.7727
FCR (II)	63.89	8.6	
SBP(I)	112.83	12.46	.9462
SBP (II)	112.61	4.82	
DBP (I)	72.78	7.16	.0034
DBP (II)	64.17	7.49	
Swimming metres (I)	459.2	157.4	.1028
Swimming metres (II)	491.1	138.3	

*Note. CRI-I: Incremental Remaining Cholesterol; CRI-II: Incremental Remaining Cholesterol; AIP: Atherogenic Index of Plasma; AC: Atherogenic Coefficient; NHDL-C: Non-High Density Lipoprotein Cholesterol; SpO_2: Oxygen saturation percentage; RHR: Resting heart rate; SBP: Systolic blood pressure; DBP: Diastolic blood pressure. *(I)pre-intervention evaluation; (II)post-intervention evaluation.*

Table 5 shows the pre- and post-intervention results for metabolic and haematocrit variables. The analyses revealed significant changes in some of these variables. Fasting glucose showed a *p*-value = .0009775, with a mean difference of 5.33 mg/dL, indicating a decrease in glucose levels after the intervention. Total cholesterol also decreased significantly (*p*-value = .02112), with a reduction in the mean from 210.22 mg/dL to 196.7 mg/dL. Finally, haematocrit showed a significant reduction (*p*-value = .001926).

Table 5. Metabolic variables and haematocrit.

Variables	**Media**	**Standard Deviation**	**T test (*p*-value)**	**I.C Medias differences**
Glucose (I)	92.67	7.23	.0009775	
Glucose (II)	87.33	5.32		2.90; 7.76
Total cholesterol total (I)	210.22	23.79	.02112	
Total cholesterol (II)	196.7	35.4		2.63; 24.48
Haematocrit (I)	43.8	4.52	.001926	
Haematocrit (II)	46.23	3.83		1.194; 3.672

*Note. *(I)pre-intervention evaluation; (II)post-intervention evaluation.*

DISCUSSION

This study sought to evaluate the effects of a 16-week apnoea training program on body composition and metabolic and cardiovascular biomarkers in university teachers, considering the importance of physical exercise on health parameters (Soto & Vargas, 2024).

The first finding was related to anthropometric and body composition variables, which showed no significant differences after apnoea training. This result could be attributed to the specific nature of apnoea training, which may not exert a significant impact on body composition over a relatively short period of 16 weeks. This finding is consistent with previous studies that have examined the effects of apnoea training on body composition in athletes without representative changes (Herrera et al., 2020; Lemaitre et al., 2015), although it differs from other studies in which training for up to 8 weeks has impacted body composition in obese women (Jaramillo & Giraldo, 2023), in women since performing exercise in situations of intermittent hypoxia, has worked as an effective strategy to decrease body weight and improve fitness (Urdampilleta et al., 2021).

However, when considering biochemical variables such as glucose, significant differences were observed before and after the training program. The changes in these biomarkers suggest that apnoea training may have metabolic and cardiovascular effects on the participants. The significant decrease in post-training glucose levels could indicate an improvement in glycaemic regulation, which is consistent with the positive effects of physical exercise on glucose metabolism (Peinado et al., 2017), similarly, other findings have evidenced positive effects on glycaemic control and HbA1c levels, including increased aerobic fitness, muscle strength, as well as the prevention of pathologies related to and derived from diabetes mellitus (Hidalgo et al., 2024).

As for total cholesterol, its post-training decrease could be related to physiological adaptations to regular exercise, such as increased lipolytic activity and muscle cholesterol synthesis (Sáez-Roca et al., 2019) emphasizing the impact of physical exercise as a crucial intervention to prevent or delay cardiovascular diseases (Insignares et al., 2024).

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On the other hand, the increase in haematocrit levels after training could be attributable to changes in blood viscosity and oxygen-carrying capacity due to repeated exposure to hypoxia during apnoea (Bakovic et al., 2003), consistent with other studies in which a significant increase in haematocrit has been observed with 4-month exercise programs (Pérez et al., 2003), 2003) suggesting that aerobic training improves oxygen delivery to body tissues and The haematocrit level also improves because of tailored exercises that measure the body's proportion of red blood cells (Ribeiro, 2024) and the other effect of apnoea exercises is that they increase the strength of smooth muscles in the respiratory system (Stevens, 2021).

In addition, significant changes in non-high-density lipoprotein (NHDL-C) were observed, which were associated with a decrease in cardiovascular risk. These findings are consistent with previous studies that have demonstrated the beneficial effects of aerobic exercise on cardiovascular health, including reduced NHDL-C (Sato & Fisher, 2018). It is relevant to consider that no changes in blood pressure were seen quite possibly as found in other studies because the dietary diet factor was not controlled for (Ramirez et al., 2024; Salazar et al., 2024) although other studies have found that 16-week exercise programs have generated changes in diastolic and systolic blood pressure in women (Gutierrez et al., 2020).

Heart rate and oxygen saturation did not show significant differences in this study as in the study by Bezruk et al. (2024) in which heart rate and SpO_2 decreased after eight weeks of diving training in athletes and sedentary participants. In the same way, they are considered predictors of peak performance in freedivers (Lee et al. 2024).

Importantly, this study is one of the few to investigate the effects of apnoea training in a population of university teachers, which highlights the importance of continuing to explore this area of research to better understand the benefits and possible risks of this type of intervention in different age groups and health conditions.

CONCLUSIONS

The study demonstrated that apnoea training can have a positive impact on the metabolic and cardiovascular health of university teachers, evidenced by significant decreases in fasting glucose, total cholesterol, and NHDL-C levels, as well as an increase in haematocrit. These changes suggest improvements in glycaemic regulation and lipid profile, which could contribute to reducing the risk of cardiovascular diseases in generally sedentary populations.

Despite the positive effects on metabolic and cardiovascular biomarkers, apnoea training did not induce significant changes in the participants' body composition, including variables such as abdominal perimeter, body fat percentage, and muscle mass. This may indicate that apnoea training, as implemented in this study, may not be sufficient to significantly alter body composition over 16 weeks.

The results highlight the need for further studies with a more robust design, including a control group and a larger sample, to confirm the effects of apnoea training in different populations. Furthermore, it is suggested to extend the duration of the training programs to explore possible long-term changes in body composition, to better understand the physiological mechanisms involved in the response to apnoea training.

Limitations

Despite these promising results, it is important to recognize the limitations of this study, including the lack of a control group and the relatively small sample size. In addition, the duration of the training program may not have been sufficient to induce significant changes in body composition. Further studies with more robust designs and longer duration are needed to confirm these findings and to better understand the effects of apnoea training on health in the group of university teachers.

AUTHOR CONTRIBUTIONS

Conceptualization and methodology: J.G-CH., O.H.J-T., A.C-O; formal analysis, investigation resources, writing—original draft preparation, review, and editing, J.G-CH., O.H.J-T.; A.F-D., A.C-O., and I.C.R.-P. All authors have read and agreed to the published version of the manuscript in JHSE.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Eating disorders: A school-based nutrition education and physical activity didactic intervention

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ABSTRACT

This study investigates the effectiveness of an integrated school-based programme aimed at improving the psycho-physical well-being of secondary school students with eating disorders (ED). Using a qualitative-quantitative approach, standardised data collection instruments were used, such as the KIDMED test to assess adherence to the Mediterranean diet, the Rosenberg Self-Esteem Scale to measure self-esteem, and the Strengths and Difficulties Questionnaire (SDQ) to monitor emotional well-being. The six-month project combined nutritional education, physical activity and psycho-educational support to promote healthy eating habits, self-esteem and balanced growth. The results show significant improvements in the parameters of psycho-pedagogical well-being, adherence to a balanced diet and participation in motor activities.
Keywords: Sport medicine, Self-esteem, Psycho-pedagogical support, Well-being, Secondary school, Health.

Cite this article as:
Gravino, G., Palmiero, F., Di Palma, D., & Tafuri, F. (2025). Eating disorders: A school-based nutrition education and physical activity didactic intervention. *Journal of Human Sport and Exercise, 20*(2), 682-693. https://doi.org/10.55860/k188b408

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Submitted for publication February 06, 2025.
Accepted for publication March 14, 2025.
Published March 26, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/k188b408

INTRODUCTION

Eating disorders (EDs) are a growing problem among adolescents, with profound effects on both physical and mental health. These disorders include a variety of conditions such as anorexia nervosa, bulimia nervosa and uncontrolled eating, which negatively affect an individual's relationship with food, body and self-perception. The prevalence of DCA has increased in recent years, particularly among adolescents, a crucial period in their physical and psycho-physical development. According to recent epidemiological studies (Smith et al, 2022; Rossi et al, 2023), DCA is often associated with complex risk factors, including social pressure, exposure to unrealistic beauty models in the media and emotional vulnerability. Increasing social pressure on adolescents, often fuelled by unrealistic images conveyed by social media, has been shown to be a significant catalyst for the development of eating disorders.

Researchers such as Thompson and Stice (2021) suggest that exposure to unattainable beauty standards can negatively affect self-esteem and promote disordered eating behaviours. Furthermore, longitudinal studies (Becker et al., 2020) have shown an association between heavy social media use and the onset of DCA, particularly among adolescent girls. Biologically, adolescence is a particularly vulnerable time. Rapid physical changes, coupled with an increase in social awareness, can increase adolescents' insecurities about their bodies. Researchers such as Ricciardelli and McCabe (2020) have shown that the way adolescents perceive body changes at this stage can significantly influence their risk of developing DCA. Schools, as the primary educational and social setting, offer a unique opportunity to implement prevention and intervention programmes.

An integrated approach combining nutrition education, physical activity and psycho-educational support can help to reduce the risk factors associated with DCA. For example, Brown et al (2021) showed that school programmes focused on nutrition education not only improved eating habits but also reduced anxiety and depression in students. Another crucial element is physical education. Studies such as García-Hermoso et al. (2022) show how regular physical activity can improve self-esteem and psychological well-being in adolescents. Team sports, in particular, have been shown to promote social cohesion and reduce feelings of isolation, an aspect often associated with DCA. The importance of family involvement in school-based prevention programmes cannot be underestimated. The literature (Tylka et al., 2019) suggests that active parental participation can amplify the effectiveness of interventions by providing ongoing support to young people outside of the school environment. Engaging families through information sessions and practical workshops can help to create a supportive environment for change.

This experimental project was designed to respond to these needs by offering an integrated and tailored approach aimed at creating a culture of global well-being in schools. The main objective was to promote healthy eating habits, increase self-esteem and improve the mental health of adolescents. The innovation of this study lies in the integration of different disciplines, such as nutrition, psychology and physical activity, into a single school curriculum. Such multidisciplinary interventions have been identified as essential to address the complexity of DCA, as suggested by recent systematic reviews (Rohde et al., 2021).

MATERIALS AND METHODS

The programme was developed over six months, with a total of 24 weekly meetings. Each session was divided into three main modules, each designed to address specific aspects of wellbeing: nutrition education, motor activities and emotional support.

The methodology was designed to ensure an integrated and personalised approach, combining tools to evaluate the effectiveness of the project, using a combination of quantitative and qualitative methods to ensure a multidimensional analysis of the results. The Rosenberg Self-Esteem Scale and the Strengths and Difficulties Questionnaire (SDQ) were used to monitor psychological progress, while the "*KIDMED Test*" measured changes in eating habits. Data analysis included descriptive and inferential statistical techniques to identify significant changes in student behaviour. This mixed approach was chosen based on scientific evidence that emphasises the importance of integrating numerical data with subjective observations to better understand complex phenomena such as eating disorders (Brown et al., 2021; Larsen, Strand & Schmidt, 2021).

The integration of these different methodologies enabled a comprehensive and multi-dimensional evaluation of the effectiveness of the project, in line with the principles of methodological triangulation promoted by recent studies (Smith et al., 2022; Brown et al., 2021).

Participants

The project involved a total of 120 students aged between 11 and 14 from four secondary schools in an urban area. Students were selected on the basis of a pre-assessment that included self-administered questionnaires and teacher observations to identify risky eating behaviours and signs of emotional distress. Particular attention was paid to students who showed early signs of DCA, such as food restriction, episodes of uncontrolled eating, or excessive preoccupation with body weight.

Measures

- Dietary lifestyle questionnaires: The KIDMED test, a widely validated tool for assessing adherence to the Mediterranean diet (Bach-Faig et al., 2011), was administered to students at the beginning and end of the project. The use of this test made it possible to identify significant variations in students' eating habits, in line with the report by Micha et al. (2020) on the importance of the Mediterranean diet in promoting well-being; customised questionnaires with five-point Likert scales to analyse specific aspects such as meal frequency, fruit and vegetable consumption and food preferences. These data provided detailed information on students' daily eating habits, as suggested by Vidgen and Gallegos (2014) for the assessment of food literacy.
- Motor activity monitoring: The documentation of motor activities was carried out through participation registers, which monitored the frequency of sessions attended by the students. Previous studies (García-Hermoso, Ramírez-Vélez & Saavedra, 2022) highlight that regular monitoring is essential to assess compliance with physical activity programmes. For a more qualitative assessment, individual cards were used to record the quality of students' participation and engagement during activities. This approach is in line with Tylka, Annunziato and Burgard (2019), who highlight the importance of considering emotional involvement in health promotion programmes.
- Physical and psychological measurements: Body mass index (BMI) was monitored at the beginning and end of the project to detect any significant changes in anthropometric parameters, as recommended by Larsen et al. (20-21). In parallel, cardiovascular endurance tests, such as the shuttle run test, were performed to assess improvements in physical fitness, in line with Bratman, Hamilton and Daily's (2015) report on the benefits of physical activity on mental and physical health. Validated psychological scales were used to assess students' emotional well-being and self-esteem. In particular, the Rosenberg Self-Esteem Scale measured levels of self-esteem, while the Strengths and Difficulties Questionnaire (SDQ) provided an overview of overall psychological well-being. These instruments are widely used in the literature to assess psychological dimensions in young people (Rohde, Stice & Marti, 2021).

- Interviews and remarks: Semi-structured interviews were conducted with a representative sample of students to explore their perceptions and experiences during the programme. The importance of incorporating qualitative interviews into school-based intervention designs has been highlighted by Ricciardelli and McCabe (2020), who emphasise the value of listening to young people's voices in order to better understand the factors that influence their behaviour. In addition, the use of personal diaries and teacher feedback enriched the collection of qualitative data and provided a more comprehensive perspective on the impact of the project. As reported by Thompson and Stice (2021), direct observations and qualitative reports can provide essential context for the interpretation of quantitative data.

Proceedings

Each session was divided into three main modules:

1. *Nutrition education*

- Theoretical and practical sessions: The sessions, led by nutritionists and psychologists, included educational elements based on scientific evidence (Micha et al., 2020). Students were taught the principles of a balanced diet, with particular emphasis on the Mediterranean diet, which is recognised for its benefits in preventing DCA (Bach-Faig et al., 2011). The teaching methodology included lectures, guided discussions and practical activities to critically analyse food labels and advertisements.
- Interactive discussions: Students analysed examples of distorted eating patterns promoted by the media. The aim was to develop critical thinking skills to identify toxic narratives that negatively influence body perceptions (Tiggemann & Slater, 2014).
- Hands-on cooking workshops: Each cooking session included moments of reflection on the benefits of seasonal and sustainable food. o Students actively participated in the preparation of balanced meals, consolidating practical and theoretical skills (Vidgen & Gallegos, 2014).

2. *Physical activity*

- Yoga and mindfulness sessions: Suggested exercises, led by certified instructors, are designed to reduce stress and increase body awareness. Research suggests that mindfulness can improve one's relationship with one's body and promote greater self-acceptance (Atkinson & Wade, 2015).
- Team sports: Sports activities such as volleyball and basketball promoted cooperation and a sense of belonging among students. According to the cooperative learning model, group dynamics can build self-esteem and reduce social isolation (Johnson & Johnson, 2009).
- Dance and creative activities: Dance classes are designed to increase positive body awareness and stimulate emotional expression. Recent studies show that dance is a powerful tool for improving mental health and body awareness (Quiroga Murcia et al., 2010).
- Walking in nature: These activities allowed students to experience psychological benefits associated with the natural environment. The literature supports the idea that exposure to nature can reduce stress levels and improve overall well-being (Bratman et al., 2015).

3. *Emotional support*

- Dialogue and listening groups: Facilitated by school psychologists, these groups provided a safe space to share feelings and difficulties. The approach used was based on the person-centred model of therapy, which emphasises empathy and unconditional support (Rogers, 1951).
- Meetings with parents: Meetings were structured to make families aware of DCA and provide practical tools to support their children. Parental involvement has been shown to be crucial in the prevention and management of DCA, as evidenced by recent research (Larsen et al., 20-21).

Analysis

The analysis of the data collected before and after the intervention showed significant improvements in several areas, highlighting the effectiveness of the strategies adopted in the project. The results were divided into four main categories: eating habits, participation in motor activities, psycho-pedagogical well-being and qualitative feedback.

RESULTS

Dietary habits

1. *KIDMED Test*

- Before: The mean KIDMED test score was 5.6 (±1.2), indicating moderate adherence to the Mediterranean diet in the majority of students.
- After: The mean score increased to 7.0 (±1.1), a significant increase of 25% ($p < .05$), indicating greater compliance with dietary recommendations.

The increased score can be attributed to the nutrition education activities, which encouraged students to prefer healthy foods and improved meal planning.

2. *Fruit and vegetable*

- Before: Only 35% of students consumed at least three portions of fruit and vegetables per day.
- After: This percentage increased to 65%, an increase of 30%.

The inclusion of hands-on workshops and the availability of healthy alternatives in school meals played a crucial role in encouraging these changes.

3. *Junk food*

- Before: 40% of students regularly consumed snacks high in sugar and fat.
- After: the percentage dropped to 20%.

This result reflects the effectiveness of educational strategies in making students aware of the negative effects of junk food.

Participation in physical activities

1. *Frequency of sessions*

- Before: Only 60% of students regularly participated in extracurricular motor activities.
- After: 87% of students attended at least 80% of the sessions during the project.

The improvement is due to the introduction of engaging activities and the creation of a motivating environment.

2. *Cardiovascular endurance (Shuttle Run Test)*

- Before: The mean cardiovascular endurance score was 6.8 (±1.5) completed steps.
- After: After the intervention, the mean score increased to 7.6 (±1.3), an increase of 12% ($p < .05$).

The improvement reflects not only increased participation, but also the inclusion of motor activities designed to gradually improve cardiovascular capacity.

Psychological Well-being

1. *Self-esteem (Rosenberg Self-Esteem Scale)*

- Before: The mean score was 18 (±3.2), indicating a moderate level of self-esteem.
- After: The mean score increased to 24 (±2.8), a significant improvement of 33% ($p < .01$).

The educational and motor activities helped to increase the students' self-efficacy and positive self-perception.

2. *Emotional Well-being (SDQ)*

- Before: 45% of students showed moderate or high emotional symptoms.
- After: The percentage dropped to 15%, recording an overall reduction of 30% ($p < .05$).

The combination of psychosocial support and mindfulness strategies had a significant impact on emotional well-being.

Qualitative feedback

1. *Students*

- Before: Many students described a lack of awareness of their eating habits and a negative perception of their bodies.
- After: Students reported greater food awareness and a more positive perception of their body image, consistent with the quantitative results on self-esteem growth.

2. *Teachers and parents*

- Before: Parents and teachers pointed out the presence of risky eating behaviour and poor social interaction among the students.
- After: A significant reduction in such behaviour and an improvement in class cohesion, due to the introduction of collaborative activities and group dynamics, was reported.

Many students highlighted a significant change in their perception of food and their daily eating habits. Before the intervention, several participants reported that they had little awareness of the quality of the food they consumed and often preferred unhealthy foods. Below are some of the sentences reported by the students: "*I used to eat packed snacks at break time, but now I bring fruit or a wholemeal sandwich from home. I have learnt that I can make healthier choices without sacrificing taste*", or "*I used to think that eating healthy was difficult, but after trying new recipes during the workshops, I realised that it is also fun*". Parents, on the other hand, report: "*We have noticed that our son asks us to buy more fruit and vegetables. His attitude towards family meals has changed and he often talks about what he has learned at school*". Finally, the teachers: "*The pupils have become more aware of their food choices. At lunchtime, we notice that many of them avoid sugary drinks and packed snacks, opting instead for healthier alternatives*".

Another of the most significant changes was observed in the students' self-image. Many reported feelings more confident about their bodies and more comfortable in social interactions: "*Before, I often felt insecure about my body. After taking part in the project I feel stronger and more confident*", "*I like seeing the improvements in my physical stamina and knowing that I am doing something good for my body*".

The physical activities and educational workshops helped to improve the social dynamics within the classes, encouraging cooperation and empathy. Pupils described a greater sense of belonging and openness to their peers: "*I really enjoyed working in groups. Not only did I learn new things about food, but I also got to know* *my classmates better*", "*The sports activities were challenging, but we encouraged each other and that brought us together*". As one teacher pointed out: The activities designed to involve all pupils helped to create a climate of inclusion. Even the shyer pupils started to participate actively.

Many students reported feeling calmer and less stressed as a result of the mindfulness strategies and physical activities included in the project: "*After the mindfulness sessions, I felt more relaxed and ready to concentrate in class*".

The project had a positive impact not only on individual students, but also on the whole school environment. Teachers and principals reported an overall improvement in the school climate, with greater student engagement and a reduction in interpersonal conflict: "*There was less tension between students. The collaborative activities have strengthened relationships and created a more harmonious environment*" and "*The project has created a sense of community, not only among students but also among teachers and families*".

Qualitative analysis was carried out through semi-structured interviews with students, the collection of personal diaries, teacher feedback and informal parental observations. The data collected provides a comprehensive picture of the impact of the project, not only on habits and behaviour, but also on emotions, self-perception and social dynamics.

The qualitative analysis revealed a number of cross-cutting improvements, ranging from nutritional awareness to psycho-pedagogical well-being, increased social cohesion and reduced stress. These changes were supported by both direct statements from the pupils and observations from parents and teachers. The combination of educational, motor and psychological approaches allowed the challenges to be addressed holistically and significant results to be achieved at multiple levels.

Analysis of the pre- and post-intervention data showed significant changes in all areas analysed. Improved eating habits, for example, can be attributed to the introduction of evidence-based nutrition education programmes, as suggested by Bach-Faig et al. (2011). Reduced consumption of junk food and increased consumption of fruit and vegetables demonstrate the effectiveness of educational strategies integrated into the school day (Vidgen & Gallegos, 2014).

Active participation in motor activities had a positive impact not only on the physical fitness but also on the psycho-pedagogical well-being of students, as evidenced by the improvement of scores related to self-esteem and reduction of emotional symptoms. These results are consistent with previous studies that highlight the importance of physical activity in promoting mental health in young people (García-Hermoso et al., 2022).

Finally, qualitative feedback provided a valuable complement to the quantitative data, highlighting how the integrated approach of the project had a positive impact not only on individuals but also on group dynamics and the overall school environment.

DISCUSSION

The project results show that the integration of educational, motor and psychological components is an effective model for addressing eating disorders in adolescents. This approach is particularly relevant because it allows for multilevel intervention, addressing both individual factors (e.g. food awareness and self-perception) and social and environmental factors (e.g. group dynamics and family support). Recent literature supports this direction, with studies such as García-Hermoso et al. (2022) and Tylka et al. (2019) showing that integrated school programmes can lead to lasting improvements in adolescents' mental and physical health. For example, nutrition education not only improved students' knowledge, but also positively influenced their self-esteem, especially thanks to the emotional support provided during mindfulness sessions. Similarly, physical activity not only improved physical fitness, but also fostered a sense of belonging and reduced stress.

One aspect that emerged during the project was the importance of tailoring activities to the specific needs of participants. Adolescents are a heterogeneous group with significant differences in motivation, food preferences and levels of physical activity. Personalised interventions, such as the use of individualised questionnaires and participation cards, proved essential to maximise the impact of the project. For example, some participants reported that being able to choose between different physical activities increased their engagement. This suggests that future interventions could benefit from greater flexibility in design, for example including options for creative or artistic activities that might attract students less inclined to traditional exercise.

The results clearly show that improved self-esteem and body image had a significant impact on the students' overall wellbeing. What is particularly interesting, however, is the cascading effect of these changes: improved self-perception has had a positive impact on interpersonal relationships, strengthening group dynamics and reducing class conflicts. The project has also helped to create a sense of community among students, teachers and families. This social element is crucial as DCAs are often associated with isolation and relationship difficulties. As highlighted by Tylka et al. (2019), family involvement is a key factor in the success of preventive interventions. In this project, constant dialogue with parents and sharing students' progress reinforced the positive impact and created a supportive environment both inside and outside of school.

Despite the positive results, it is important to recognise some of the limitations of the project. For example, the relatively short duration of the intervention does not allow for a full assessment of the long-term impact on students' eating habits and psycho-pedagogical well-being. Another challenge is the commitment required from teachers and school staff, who need to be properly trained to integrate complex activities such as mindfulness or nutrition education workshops into the school curriculum. This highlights the need to invest in staff training and the development of accessible teaching materials.

To broaden the impact of similar programmes, it is important to develop models that are easily scalable and adaptable to different contexts. This could include the use of digital technologies, such as apps to monitor eating habits and physical activity, or online platforms for emotional support and mindfulness. In addition, collaboration with health institutions and local communities could strengthen the sustainability of interventions by ensuring adequate resources and continuity over time. Another interesting direction is research into the impact of digital culture and social media on adolescent eating behaviour. Recent studies, such as Tiggemann and Slater (2014), show that media exposure can significantly influence body perceptions and eating habits. Future interventions could include educational sessions to promote critical and conscious use of social media, helping adolescents to develop greater resilience to harmful messages about beauty and nutrition.

Finally, the project highlighted the importance of a systemic approach, involving not only students and teachers, but also families, health professionals and school policy makers. The implementation of school policies that promote healthy lifestyles, such as the introduction of healthy food options in school canteens or the promotion of active breaks during the day, could enhance the impact of preventive interventions.

CONCLUSION

The project described provided a detailed and multidimensional view of the effectiveness of an integrated approach to the prevention and management of eating disorders in adolescents. The results not only confirm the validity of the strategies adopted but also highlight important considerations about the role of schools, families and communities in promoting the mental and physical well-being of young people.

A key message from this project is the importance of early intervention. Adolescence is a particularly sensitive period when behaviours and habits develop that can affect long-term health. Previous studies, such as those by Ricciardelli and McCabe (2020) and Rohde et al. (2021), have shown that intervention at this stage of life is particularly effective in preventing the onset of DCA and other related problems, such as overweight or obesity.

Our project has shown that a combination of nutrition education, physical activity and psychoeducational support can significantly change eating habits, improve self-perception and reduce risk factors associated with DCA. This suggests that investing in prevention programmes in schools could be a long-term strategy to reduce the health and social burden associated with these problems.

The potential replicability of the project is a key aspect of the project. The methods used, such as the use of the KIDMED test, guided motor activities and mindfulness sessions, have been designed to be easily implemented in different school settings. However, to ensure success, it is essential to take into account the cultural, economic and social specificities of each context.

For example, schools in low-income or resource-poor areas may need to make changes to adapt the project to the resources available. In these cases, one possible approach could be to work with NGOs or local authorities to provide additional support. In addition, the integration of digital technologies is an interesting prospect for further widening the scope of interventions. Educational apps, online platforms for monitoring dietary habits and physical activity, or gamification tools could increase student engagement and encourage greater adherence to the programme.

Another important finding is the confirmation of the value of a holistic approach to adolescent wellbeing. We have not only considered the nutritional or physical aspects but have also given ample space to emotional support and building positive relationships between students, teachers and families. This approach was crucial to the success of the project, as evidenced by significant improvements in students' self-confidence and psycho-educational well-being.

The mind-body connection, often overlooked in more traditional interventions, has proved crucial. Mindfulness, in particular, has played a key role in promoting greater awareness of food choices and better control of emotions. As Giordano et al. (2022) point out, these practices not only improve psychological well-being, but can also have a positive impact on eating behaviour and interpersonal relationships.

Despite the positive results, the project highlighted some challenges that deserve attention. One of the main difficulties was to ensure the active participation of all students, especially those with lower initial motivation. This underlines the importance of personalised approaches that take into account the different needs and preferences of students. Another challenge is the long-term sustainability of the interventions. For a project such as this to have a lasting impact, it is essential that it is integrated into school policy and supported by adequate resources. This requires a joint commitment from schools, health authorities and local communities.

The results of the project open up a number of research questions that could be explored in future studies. For example: What are the long-term effects of similar interventions on adolescents' lifestyles and health? How do cultural differences affect the effectiveness of DCA prevention programmes? What factors determine the sustainability and scalability of these interventions? In addition, future research could focus on using new technologies, such as artificial intelligence, to further personalise interventions and monitor students' progress in real time.

Finally, the success of this project highlights the need for greater political and social commitment to addressing DCAs and promoting healthy lifestyles. School policies that promote nutrition education, regular physical activity and psychological support should not be seen as a luxury, but as an essential part of education.

Promoting a school environment that supports students' well-being not only improves their health but can also have a positive impact on their academic performance, social relationships and future active participation in society.

In conclusion, the project represents a promising model for addressing adolescent BDA through a multidimensional and integrated approach. While acknowledging the challenges and limitations, the results highlight the importance of investing in early prevention and adopting innovative and holistic strategies to promote adolescents' mental and physical well-being. Only through collective commitment and coordinated action can we hope to build a healthier, more aware and resilient generation.

AUTHOR CONTRIBUTIONS

The authors actively collaborated in the realisation of the study and the drafting of the manuscript, contributing at different stages of the research. Specifically: Gianluca Gravino oversaw the general coordination of the study, methodological design and data collection, as well as supervising the analysis phase; Fabiola Palmiero contributed to the literature review, the design of the educational activities and the drafting of the sections on nutrition and psychological support; Davide Di Palma participated in the implementation of the physical activity programme, the collection of data on students' motor participation and the evaluation of the impact on physical performance; Francesco Tafuri provided support in data analysis, discussion of results and final revision of the manuscript. All authors have read and approved the final version of the article and declare that they have no conflicts of interest.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Effects of high intensity interval training and resistance training on blood pressure and heart rate variability in young subjects

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ABSTRACT

High-intensity training, including resistance training (RT) and high-intensity interval training (HIIT), has demonstrated acute change cardiovascular on blood pressure (BP) and heart rate variability (HRV).This study aimed to analyse the acute effects of RT and HIIT on BP and HRV among young adults. This study used a crossover trial design conducted with 15 participants (19–25 years old). Participants underwent RT and HIIT sessions. BP systolic (SBP), diastolic (DBP), and mean arterial pressure (MAP) and HRV (SDNN, RMSSD, pNN50) were measured at baseline (pre), immediately post-intervention (post), and after 8 minutes of recovery (post 8 min). The results showed that both types of training significantly increased SBP and DBP immediately post-exercise ($p < .001$). DBP demonstrated a significant reduction at post 8 min for RT ($p = .003$). HRV indices showed significant reductions post-intervention in both training modalities (SDNN: RT, -11.6 ms; HIIT, -26.1 ms; $p = .01$). HIIT resulted in greater decreases in HRV parameters compared to RT ($p = .01$). In conclusions, RT and HIIT elicit significant acute changes in BP and HRV, with HIIT demonstrating a more pronounced impact on autonomic modulation. These findings highlight the differential cardiovascular responses to high-intensity training modalities and suggest potential implications for exercise prescription.
Keywords: Sport medicine, High-intensity interval training, Resistance training, Blood pressure, Heart rate variability, Autonomic modulation.

Cite this article as:
Benavides-Roca, L., Miranda, M., Hernández, S., Vega, A., Campos, L., Benavides, M., & Benavides, G. (2025). Effects of high intensity interval training and resistance training on blood pressure and heart rate variability in young subjects. *Journal of Human Sport and Exercise, 20*(2), 694-705. https://doi.org/10.55860/qepkyn98

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Submitted for publication February 06, 2025.
Accepted for publication March 19, 2025.
Published March 26, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/qepkyn98

INTRODUCTION

Cardiovascular health is rooted in an epidemiological context where lifestyle factors, sedentary behaviour, and physical inactivity contribute to a progressive decline in cardiac function (Van Deutekom & Lewandowski). Within this framework, cardiovascular diseases stand out as some of the most prevalent pathologies, with high rates of morbidity and mortality worldwide (Troncoso-Pantoja et al., 2020). In Chile, the factors associated with the development of cardiovascular diseases are particularly concerning. The elevated risk of arterial hypertension (Petermann et al., 2017), combined with high levels of physical inactivity and a significant prevalence of obesity, presents a worrisome scenario that underscores the urgent need for strategies to mitigate these risks and improve cardiovascular outcomes.

Exercise is an effective non-pharmacological intervention to address cardiac pathologies (Lellamo et al., 2021), as well as being a relevant physiological parameter for improving clinical criteria in patients with these conditions (Ross et al., 2016). Epidemiological studies have shown an inverse relationship between the practice of physical activity and the incidence of cardiovascular disease and mortality associated with these causes (Cotignola et al., 2023). Exercise is also a beneficial strategy for promoting cardiovascular health (Son et al 2016) by improving arterial pressure and elasticity arterial (Jeon, Lee & Hwang et al., 2018; Figueroa et al., 2014). This evidence demonstrates the ability of the heart to adapt to constant stimuli and to produce positive changes at a structural and physiological level.

This evidence shows that exercise should be an essential part of cardiovascular health care. Resistance training (RT) is an effective option for improving cardiorespiratory fitness as it increases maximum cardiac output, peak stroke volume, accelerates DBP filling and delays left ventricular remodelling (Moris et al.,2020). Similarly, high-intensity interval training (HIIT) has been shown to have a positive effect on cardiovascular capacity through the alternation of submaximal intensity activation and recovery periods. This alternation promotes cardiovascular efficiency, which is reflected in HRV during the intervals (Abreu et al., 2019).

During exercise, cardiac function undergoes transient autonomic adjustments through sympathetic and parasympathetic modulation, influencing BP and heart rate dynamics (Mariano et al., 2022). These responses are essential for maintaining cardiovascular homeostasis during increased metabolic demands. Research has demonstrated that there is an increase in cardiac output immediately following exercise, resulting in elevated BP (Nayor, Gajjar & Murthy, 2023). However, this effect is transient, as autonomic recovery ensues during the repose phase, leading to a decrease in BP and an increase in HRV (De Brito et al., 2019; Mongin et al.,2020). These processes are of paramount importance because the heart plays a pivotal role in responding to energy demands, which are regulated by the balance of the autonomic system (Mongin et al.,2020). This, in turn, controls heart rate and R-R wave interval fluctuations, which have been shown to be relevant to cardiovascular health. Autonomic dysfunction is associated with cardiovascular disease, sudden death and mortality from all causes (Costa, 2020). However, it has been demonstrated that high intensity exercise exerts a beneficial effect on responses in cardiac autonomic modulation and cardiac biomarkers (Wang et al., 2024).

Existing evidence supports the efficacy of exercise in producing beneficial adaptations in the body. However, there is a need to further investigate how the cardiovascular system responds from a comprehensive perspective that includes both vascular and central components, particularly in relation to different types and intensities of exercise. Despite the established benefits of high-intensity exercise, little is known about the acute cardiovascular responses to RT and HIIT in healthy young adults, particularly in terms of short-term autonomic modulation and hemodynamic recovery. Understanding these acute responses is essential for designing appropriate exercise stimuli to promote cardiovascular health, optimize exercise prescriptions, and minimize cardiovascular risk across diverse populations. Therefore, this study aims to analyse the effects of RT and HIIT on cardiovascular responses in young individuals.

METHODS

Participants

Sample size was calculated using a sample size calculator for reliability studies. Based on data from Wang et al (2024), a minimum acceptable intraclass correlation coefficient (ICC) of 0.8, a power of 90% and two replicates per participant (k = 2) yielded a required sample size of 14. The participants are young people aged between 19 and 25 years (5 females and 9 males). Subjects were selected through a non-probabilistic convenience sampling method. Inclusion criteria required participants to have controlled BP (<130/80 mm Hg at rest). Exclusion criteria included having a chronic non-communicable disease (e.g. hypertension, diabetes, cancer, respiratory disease), a lower or upper limb injury that would prevent participation in resistance or interval training, or a medical contraindication to exercise.

It is important to note that the entire assessment process in this research followed the ethical guidelines established by the Ethics Committee of the University of Santo Tomas (CEC Accredited Res. No. 23136643/2023).

Protocol

This research used a randomized, single-blind, crossover clinical trial design. consisted of two training sessions: RT and HIIT (fig 1). The evaluation and control of the interventions were conducted between March and August 2024 at the Bodybuilding Laboratory of the University of Santo Tomas.

The protocol was the same for both interventions. Upon arrival at the laboratory, participants underwent baseline measurements of BP (pre) and HRV (pre), for 8 minutes lying supine on a stretcher. Following these measurements, completed the assigned intervention. Immediately after the end of the session, blood pressure was measured again (Post). After they had a period recovery of 8 minutes (Post 8 min), during which cardiovascular variables were measured again.

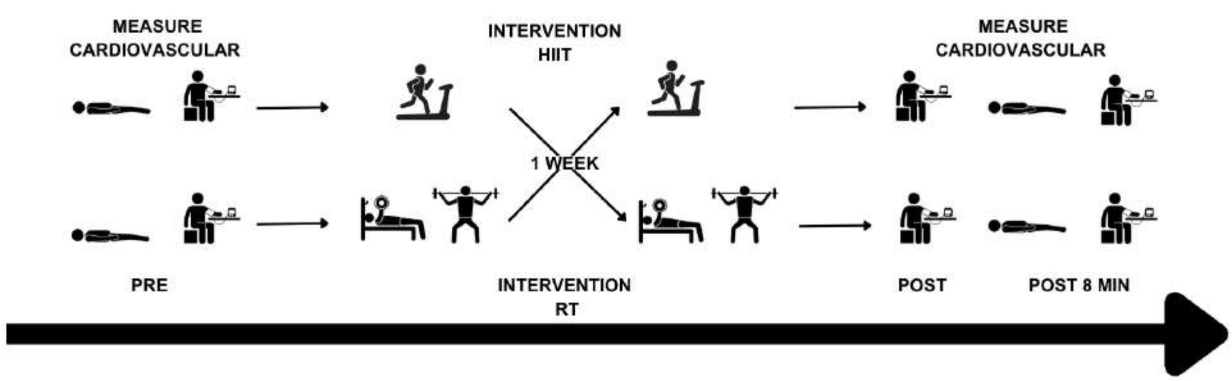


Figure 1. Protocol of intervention (Illustration created by the author).

Participants attended the laboratory on three separate occasions. During the first visit, they were informed about the experimental procedures, and their eligibility was confirmed according to the inclusion criteria.

Participants signed informed consent forms and familiarized themselves with the training sessions. In addition, anthropometric measurements were taken using a calibrated scale (Seca model 720, Hamburg, Germany).

Randomization

Randomization was performed during the second visit to the laboratory using an opaque envelope containing the assigned training type (RT or HIIT). On the same day, participants completed the session indicated on the envelope. After a one-week washout period, participants returned to complete the alternate training session. A second investigator, blinded to the training session, performed all assessments. Despite the use of an automated device to measure BP and HRV, precautions were taken to avoid any influence from the assessors.

Cardiovascular variables

HRV was measured during the pre-exercise (PRE) and recovery phases (POST 8 MIN). During both periods, participants lay supine on a stretcher for 8 min and data were collected using a Polar V800 heart rate monitor paired with an H10 sensor (Trevesini et al., 2018). R-R intervals were analysed using *Kubios* software version 3.3.1. Key metrics included the standard deviation of the intervals (SDNN), the natural logarithm of the root mean square of the consecutive differences between adjacent R-R intervals (ln RMSSD), and the percentage of R-R interval pairs that differed by more than 50 milliseconds (PNN50%).

BP was measured during the pre-exercise (PRE), immediately post-exercise (POST) and recovery period (POST 8 MIN). Participants were seated comfortably, and measurements were taken using a sphygmomanometer (Omron HEM-907, Healthcare, Tokyo, Japan) placed on the left arm near the elbow. SBP, DBP and MAP were recorded. MAP was calculated using the formula: $([2 \times DBP] + SBP) \div 3$.

RT intervention

The session began with a warm-up focusing on free weight exercises, including squats and bench presses, performed at light loads for 10-15 repetitions. Participants then performed up to three sets of two repetitions for each exercise at maximum velocity to determine the load corresponding to approximately 80% of their one-repetition maximum (squat >0.7 m/s, bench press >0.58 m/s) (Hernandez-Belmonte et al., 2023). This measurement was made using a linear transducer (ADR®, Castilla, Spain). If the target velocity was not reached within three sets, the session was postponed to the following day.

Once the appropriate load was determined, the participants performed the RT session, which consisted of four sets of six repetitions performed within the established speed parameters of exercise squats and bench presses.

HIIT intervention

The session began with a 5-minute warm-up on a treadmill at an intensity below 70% of the participant's maximum heart rate (HRmax). Following the warm-up, running speed was calibrated based on heart rate, during which the participant ran at a speed higher than that of the warm-up, reaching at least 80% of their HRmax. Once the appropriate speed was determined, the participant completed six continuous high-intensity sprints, each lasting 20 seconds, with 40 seconds of rest between sprints.

It is important to note that HRmax was estimated using the formula: 220 minus the participant's age (Robergs and landwehr, 2002). Additionally, throughout the intervention, heart rate was monitored in real time using the Elite HRV app. This allowed for immediate adjustments to the running speed to ensure the intensity aligned with the desired target.

Statistical analysis

The SPSS statistical programmer version 21 (IBM, USA) was used for data analysis. In the case of HRV, the multiple imputation method was used to estimate missing values (less than 15% of the total) based on fully observed variables. After this procedure, the Shapiro-Wilk test was performed to check the normality of the sample.

A two-factor repeated measures ANOVA was used to analyse the cardiovascular variables, comparing the interactions between time (pre vs. post, pre vs. post 8 min, post vs. post 8 min) and type of training (RT vs. HIIT). The Greenhouse-Geisser correction was used to adjust for sphericity, as the Mauchly test was significant for the variables analysed. The level of statistical significance was set at 5%.

RESULTS

The Table 1 shows the descriptive data of the subjects. Observed values demographic anthropometric (weight, height and body mass Index), indicators auto perception of activity physical (type of activity and number of days) and parameters baseline cardiovascular (heart rate and BP).

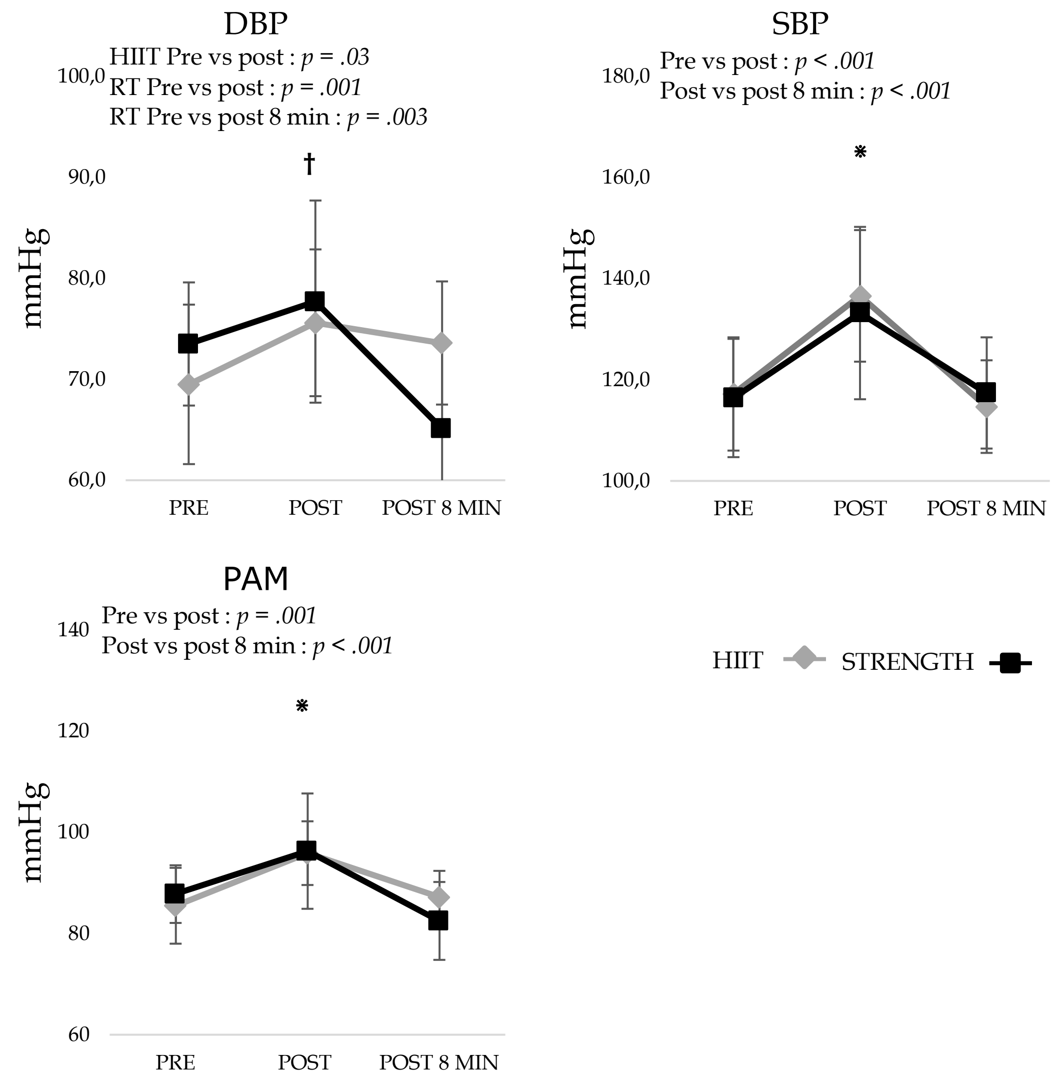
Table 1. Descriptive statistics.

Variable	**Data**
Age (years)	21.3 ± 2.8
Male/female	5/9
Weight (kg)	66.6 ± 8.1
Height (cm)	168.8 ± 7.0
Body Mass Index (kg/m2)	23.4 ± 3.0
physical activity (day in week)	3.1 ± 1.2
Type activity sport	64.3%
Type activity health	35.7%
Baseline heart rat	68.9 ± 10.8

The Figure 2 shows the behaviour of BP during the two types of high-intensity training. For SBP, no significant differences were observed in the interaction between time and training. However, the main effect of time ($F_{1,13}$ = 0.24, *p* = .78) showed significant changes, with an increase in SBP from pre- to post-measurement (p < 0.001) and a subsequent decrease from post- to 8-minute measurement (*p* < .001).

For DBP, significant interaction were observed between time and training ($F_{1,13}$ = 5.9, *p* = .01). Specifically, HIIT training showed an increase from pre- to post-measurement (*p* = .03), while RT showed a significant increase immediately post-training (*p* = .001), followed by a decrease after 8 minutes compared to the previous value (*p* = .03).

MAP showed a similar pattern to SBP, with a significant increase immediately after the intervention (p = .001) and a significant decrease at 8 minutes post-exercise compared to the immediate post-measurement (p < .001).



Note. ⁎ Significant time differences; † significant time/training differences.

Figure 2. Behaviour of blood pressure during the two protocols of high-intensity training.

The Table 3 presents the HRV data in the time domain, categorized by the effects of the training interventions. All variables showed significant differences in the time*training interaction: SDNN ($F_{1,13}$ = 9.2; *p* = .001), RMSSD ($F_{1,13}$ = 24.8; *p* < .001), and PNN50 ($F_{1,13}$ = 8.9; *p* = .01).

For SDNN, a significant decrease was observed in RT (11.6 ms; *p* = .01; d = 0.8) and in HIIT (26.1 ms; *p* < .001; d = 1.8). Regarding RMSSD, HIIT resulted in a decrease of 31.6 ms (*p* < .001; d = 2.4), while RT showed a reduction of 13.3 ms (*p* = .004; d = 1.0). Similarly, PNN50 exhibited a significant decrease over time for both RT (9.6%; *p* = .01; d = 0.9) and HIIT (1.6%; *p* = .001; d = 1.6).

It is important to note that pre-training values for all variables showed no significant differences, indicating consistency in the subjects' baseline HRV regardless of the time of evaluation. However, in the post-training measurements, HIIT resulted in lower HRV values compared to RT.

Table 3. Comparation of heart rate variability.

	HIIT	RT	Delta (HIIT – RT)	*p*-value
SDNN (ms)				
Pre	52.7 ± 15.1	51.3 ± 15.8	1.3 ± 6.8	.46
Post	26.6 ± 12.7⁎	39.7 ± 15⁎	-13.1± 2.3	.01
Ln RMSSD (ms2)				
Pre	3.6 ± 0.1	3.4 ± 0.1	0.1 ± 0.3	.10
Post	2.1 ± 0.1⁎	3.1 ± 0.1⁎	-1 ± 0.1	<.001
pNN50 (%)				
Pre	19.6 ± 14.6	16.7 ± 14.4	2.9 ± 8.1	.2
Post	1.6 ± 3.8⁎	7.1 ± 6.8⁎	-5.5 ± 3	.01

Note. ⁎ Differences significative between pre vs post with p < .05.

DISCUSSION

The aim of this study was to analyse the behaviour of the cardiovascular system during RT and HIIT. The main outcomes indicate an immediate increase in BP after the intervention, followed by a decrease after 8 minutes in the case of RT. In addition, HRV decreased 8 minutes post-exercise in both types of exercise, with a smaller reduction observed in the resistance exercise.

These results are supported by the literature, as the post-exercise increase in BP is attributed to an increase in blood flow to the activated muscles (Nayor et al., 2023). This hypertensive response aligns with findings from Corte et al (2020), which indicate that RT leads to an immediate rise in BP, with SBP increasing by approximately 20 mmHg and DBP by 10 mmHg. Similarly, HIIT has been shown to significantly elevate MAP compared to baseline value and control group (Liu et al., 2024). These results suggest that BP changes are primarily driven by the physiological demands of exercise rather than the specific training modality.

After 8 minutes, DBP decreased following RT compared to baseline, a response attributed to post-exercise vasodilation, a well-established mechanism that facilitates cardiovascular recovery and adaptation (Mariano et al., 2022). While our study observed this effect primarily in DBP, Lemos et al. (2018) reported reductions in both SBP and DBP with similar exercise protocols. These findings suggest that blood pressure changes depend on exercise load and individual vascular responses.

The variation in pressure during cardiac filling is a response that is observed to occur in the context of cardiovascular health training and is considered to be a normal consequence of the training stimulus. In study of Ashton et al. (2020) show that that high-intensity RT significantly improves health in adults at risk cardiovascular, primarily through the hypotensive effect. Thus, the reduction in BP following RT contributes to an optimal health state. When practiced regularly, it could lead to myocardial relaxation, enhanced autonomic modulation, and improved endothelial function (Guillem et al 2020). Additionally, vascular benefits such as increased nocturnal vasodilation and reduced nocturnal BP have been observed (Cardozo, 2022).

Building on the above findings, the data revealed significant differences between the values recorded immediately after training and those measured 8 minutes post-session, irrespective of the type of stimulus. This projects a hypotensive effect and highlights the potential long-term influence of training on BP regulation. However, our hypothesis was that DBP and MAP would also exhibit this behaviour, with HIIT exerting a greater influence on pressure reduction. This assumption is supported by literature indicating that HIIT induces hypotensive effects across all pressure variables (Boeno et al.,2019; Edwards et al., 2021). It is important to note that studies reporting hypotensive effects on SBP (Lemos et al., 2018; Boeno et al., 2019, Edwards et al., 2021) typically employed rest periods exceeding 10 minutes. Therefore, the shorter recovery time used in the present study may have been insufficient to detect post-exercise hypotension across all variables.

HRV significantly decreased between baseline and 8 minutes post-exercise, reflecting the expected transient shift towards sympathetic dominance during recovery (Polli et al., 2019). This response is consistent with previous (Wang et al., 2024) findings suggesting that the decrease in HRV after exercise is a natural consequence of autonomic rebalancing, rather than exercise-induced fatigue alone. According to Chen et al. (Chen et al., 2011) this temporary autonomic shift reflects the cardiovascular system's effort to meet metabolic demands and gradually restore homeostasis following high-intensity exertion.

The temporal variables and the types of training, the results of the present study showed significant differences in the values after 8 minutes, with RT causing a smaller decrease in the values of RMSSD, SDNN and PNN50%. Our findings align with those of Marasingha-Arachchige et al. (2022), which reported a significant decrease in RMSSD up to 30 minutes post-RT, with training volume identified as the most influential variable. Specifically, decreases in LNRMSSD (≈ 1 ms) were observed 15 minutes after RT involving 75% of a one-repetition maximum in exercises such as the squat, bench press, and deadlift (Kingsley et al., 2018). Similarly, a study by Flatt et al. (2019) demonstrated a decrease in Ln RMSSD following this type of training, however values returning to normal after 24 hours of recovery. For its part, HIIT produces a significant immediate decrease in Ln RMSSD that persists for more than 30 minutes (Wang et al., 2024). These findings are consistent with the results of the present study, where HIIT induced a greater reduction in HRV values after exercise. This suggests that the time required to return to basal autonomic balance may be longer after HIIT compared to RT, therefore the magnitude of change imposed by HIIT suggests greater autonomic demands.

For the PNN50% and SDNN parameters, significant reductions were observed 8 minutes post-exercise in both training sessions. in study by Kassiano et al. (2021) reported similar reductions, lasting up to 30 minutes after performing strength exercises to muscular failure, particularly during the squat exercise. Likewise, HIIT also induces reductions in these parameters, but values typically return to baseline levels within one hour (Burma et al., 2020). According to study by Seo et al, the SDNN returned to normal 60 minutes after performing HIIT for 40 seg and 200 seconds of recovery, but the PNN50% returned to normal after 30 minutes. This difference in the time to return to normal is due to the low influence of the sympathetic system on the PNN50%, so that the values are recovered earlier, as the parasympathetic system tends to position itself during the recovery phase. According to the study by Seo et al., SDNN returned to baseline 60 minutes after completing a HIIT session consisting of 40-second efforts with 200-second recovery periods. In contrast, PNN50% normalized after 30 minutes. This difference in recovery time is likely due to the lower sympathetic influence on PNN50%, allowing for a faster return to parasympathetic predominance during the recovery phase (Seo et al., 2024).

The greater HRV reduction after HIIT compared to RT suggests a stronger autonomic response, likely due to prolonged sympathetic activation during high-intensity intervals. While this is a normal physiological adaptation, it highlights the need for careful monitoring in individuals with pre-existing cardiovascular conditions. In contrast, RT may provide a more controlled autonomic stimulus, making it a potentially safer option for populations at risk of hypertension or autonomic dysregulation. Tailoring exercise prescriptions based on individual cardiovascular profiles could help optimize training adaptations while minimizing potential risks.

CONCLUSION

High intensity training, whether RT or HIIT, induces changes in hemodynamic variables. Blood pressure parameters increased immediately after both training sessions. Specifically, RT induced a hypotensive effect on DBP during the recovery period, while HRV significantly decreased after both training modalities, with HIIT causing a more pronounced reduction than RT. This decrease reflects the expected autonomic shift towards sympathetic dominance during exercise, followed by a gradual parasympathetic reactivation during recovery.

These findings highlight the importance of considering individual cardiovascular profiles when prescribing exercise, particularly for populations at risk of hypertension or autonomic dysregulation.

AUTHOR CONTRIBUTIONS

Luis Benavides, Maritza Miranda, Sebastian Hernández and Alfonso Vega contributed to the conception and design. María Benavides, Luis Campos, Luis Benavides and Maritza Miranda contributed to data acquisition and data interpretation of the work. Sebastian Hernández, Alfonso Vega and Gloria Benavides drafted the manuscript. María Benavides and Gloria Benavides critically revised the manuscript.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ACKNOWLEDGEMENTS

This study was part of final work title of science of sport and physical activity in university Santo Tomas, Chile. Therefore, we would like to thank the students and participants of the study who made this research possible.

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REVIEW ARTICLE

Physical effects of α-methyl guanidine acetic-acid consumption: A systematic review

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ABSTRACT

Creatine, a natural compound extensively studied in exercise physiology and sports medicine, has proven to be effective in enhancing physical performance, especially in high-intensity and short-duration activities. Its supplementation promotes increased muscle strength, power, and accelerates post-exercise recovery. This review aims to analyse the most recent scientific advances regarding the use of creatine in sports, analysing its ergogenic efficacy and exploring its potential to optimize performance and muscle adaptation across many athletic disciplines. A systematic review was conducted on the benefits of creatine in physical performance, using Scopus and Web of Science databases due to their academic rigor and prestige. Starting with 1,696 publications, strict exclusion filters were applied: removal of duplicates, selection of studies from the past five years, filtering by language (English and Spanish), and document type. Ultimately, 9 relevant studies were retained, selected for their quality and ranking in the top quartile of the SJR index. These studies form the final corpus for analysis in this review. Creatine supplementation enhances high-intensity performance by improving ATP regeneration, strength, and endurance. It increases muscle power during fatigue, as observed in young athletes, and boosts performance in resistance exercises like bench press by increasing repetitions and total work. Creatine also reduces fatigue and improves recovery between sets. Additionally, it positively affects body composition and VO2 max, demonstrating its effectiveness in both strength and endurance sports. Creatine supplementation consistently enhances physical performance in high-intensity activities by accelerating ATP regeneration and reducing fatigue. It also increases muscular endurance, aerobic capacity, and muscle mass. These findings position creatine as a safe and effective ergogenic aid, supporting its use to optimize both performance and recovery across various athletic contexts.
Keywords: Creatine supplementation, Physical performance, High-intensity activities, Muscle strength.

Cite this article as:
Zevallos-Aquije, A., Maravi-Cardenas, A., Salas-Bolaños, R. A., Zevallos-Aquije, A., & Palomino-Salcedo, K. (2025). Physical effects of α-methyl guanidine acetic-acid consumption: A systematic review. *Journal of Human Sport and Exercise, 20*(2), 706-714. https://doi.org/10.55860/9kxt1b42

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Submitted for publication October 24, 2024.
Accepted for publication December 08, 2024.
Published March 26, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/9kxt1b42

INTRODUCTION

Creatine, also known chemically as N-methyl guanidine acetic acid, has been extensively studied in the fields of biochemistry, exercise physiology, and sports medicine. Although it is a natural compound in the body, its significance goes beyond simply being an energy source. It is primarily known for enhancing physical performance, especially in high-intensity, short-duration activities. Its use has gained popularity among athletes and fitness enthusiasts due to its ergogenic effects, which translate into increased muscle strength, power, and post-exercise recovery (Wax et al., 2021). This compound mainly works by increasing the availability of phosphocreatine in the muscles, enabling faster production of ATP, the primary energy source during anaerobic exercise (Tarnopolsky, 2010; Poli et al., 2019).

Recent research indicates that creatine not only increases maximal strength but also improves muscular endurance, even in the absence of direct changes in maximal strength (Furtado, 2024; Mills et al., 2020). Furthermore, creatine has been observed to mitigate neuromuscular fatigue, allowing athletes to maintain optimal performance during prolonged periods of exercise (Abdalla et al., 2022). The effectiveness of creatine also depends on the timing of its administration. Studies suggest that post-workout consumption may be more beneficial than pre-workout, as it maximizes muscle absorption and utilization (António & Ciccone, 2013); however, these studies are still under debate. It is important to understand that the response to creatine supplementation varies according to individual factors such as diet, training type, and genetics (Vieira et al., 2020). Collectively, research has shown that creatine can significantly improve maximal strength and muscular endurance, especially in high-intensity, short-duration activities (Mielgo-Ayuso et al., 2019), and that a post-workout consumption strategy seems to optimize these benefits, reinforcing the previously mentioned idea. Given the aforementioned, it is necessary to conduct a thorough analysis to confirm the conclusions drawn about this compound.

A recent review of studies helps address and clarify common myths and misunderstandings about creatine, such as its safety and efficacy in different usage contexts (António et al., 2021; Macêdo & Silva, 2023). With the growing interest in nutritional supplementation, it is essential to provide evidence-based information that helps consumers and stakeholders make informed decisions regarding the use of this compound. Conducting an updated review on physical performance when consuming creatine, particularly from a sports perspective, is crucial due to the growing body of scientific evidence supporting its ergogenic effects and its application across various athletic disciplines. Over the past five years, research has advanced significantly, providing new insights into how creatine can optimize physical performance, enhance recovery, and contribute to muscle adaptation in different types of athletes under various modalities (Mielgo-Ayuso et al., 2019; Solis et al., 2021; Stares & Bains, 2020).

METHODS

The project included a systematic review of a variety of studies published to date, focusing on the scientifically evidenced benefits of creatine (α-methyl guanidino-acetic acid) consumption in relation to physical performance. For data collection, the two most recognized scientific databases, Scopus and Web Of Science, were used due to the rigor of their academic indexing and the inclusion of high impact journals, which makes them highly prestigious databases. In both cases, the following search commands were applied: in Scopus, "*creatine*" OR "*N-methyl guanidine acetic acid*" AND "*performance*" AND "*effects*" AND "*physical*," which resulted in 1,246 publications; and in Web of Science, ("*creatine*" OR "*N-methyl guanidine acetic acid*") AND "*performance*" AND "*effects*" AND "*physical*," with a total of 450 publications.

For this review, a total of 1,696 publications were initially identified. During the filtering process, strict exclusion criteria were applied to ensure the relevance and quality of the final content. First, 241 duplicate publications were removed. Next, 860 publications older than five years were discarded, as the nature of this review seeks to provide a scientific update on results, hence the five-year filter. A language filter was also applied, retaining only publications in English and Spanish, leading to the exclusion of an additional 15 documents. Finally, the document type was limited to academic articles, resulting in the elimination of 127 publications.

As a result of these filters, 453 publications remained, which were subjected to a detailed analysis of their abstracts, keywords, themes, and areas of research, leading to the exclusion of an additional 436 publications. Ultimately, 17 publications were considered relevant in terms of thematic focus, relevance, and objective results. From this group, and applying a strict criterion based on the quality of the journal and its ranking in the top quartile of the Scimago SJR index, 9 publications were selected to constitute the final corpus for this review.

Figure 1 shows the PRISMA flowchart that summarizes the study selection process. From an initial search of 1,696 publications, exclusion filters reduced the number of studies to 9 selected for this review. The diagram provides a clear visual representation of the systematic approach followed to ensure the quality and relevance of the included articles.

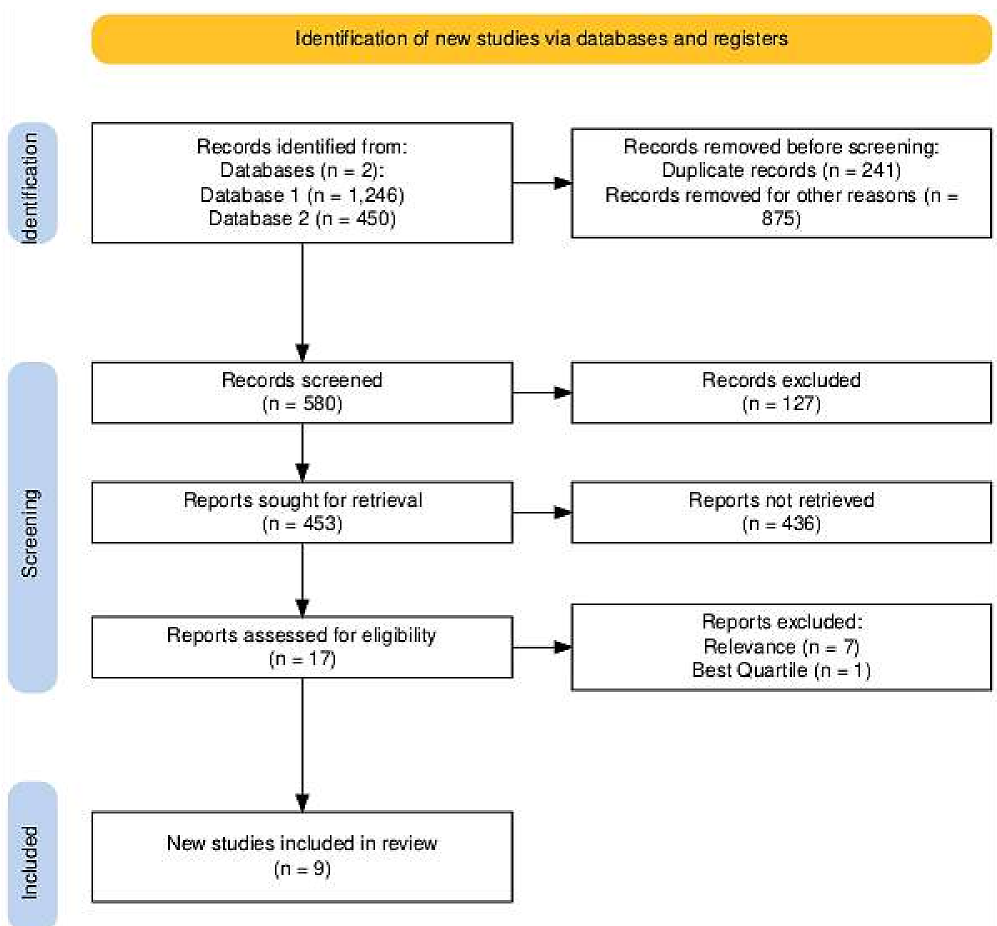

Figure 1. PRISMA flowchart - Inclusion research.

Table 1. Summary of the key reviewed studies.

Authors	Titles	Source/Scimago Best Quartile	Year	Dose	Performance
Ojeda, AH; Jofré-Saldía, E; Torres-Banduc, M; Maliqueo, SG; Barahona-Fuentes, G; Acevedo, CC; Romero, GL; Garduño, RD; Vera, GR; Paredes, PV; Avalos, BB; Serey, TM; Yeomans-Cabrera, MM and Jorquera-Aguilera, C	"Effects of a Low Dose of Orally Administered Creatine Monohydrate on Post-Fatigue Muscle Power in Young Soccer Players".	"Nutrients"/Q1	2024	The creatine (Cr) dose was 0.3 g per kilogram of body weight per day, dissolved in 200 mL of water, and taken between 18:00 and 20:00 h for 14 days. Participants were instructed to consume it with a carbohydrate-rich meal to optimize absorption.	Creatine supplementation, at a dose of 0.3 $g \cdot kg^{-1} \cdot day^{-1}$ for 14 days, significantly improved muscle power, particularly under conditions of acute intra-session fatigue, by enhancing the ability to maintain and generate strength and power. This effect was driven by increased intramuscular phosphocreatine saturation, which enabled faster ATP regeneration, leading to improved overall physical performance in young soccer players.
Maicas-Pérez, L; Hernández-Lougedo, J; Heredia-Elvar, JR; Pedauyé-Rueda, B; Cañuelo-Márquez, AM; Barba-Ruiz, M; Lozano-Estevan, MD; Garcia-Fernández, P and Maté-Muñoz, JL	"Effects of Creatine Supplementation after 20 Minutes of Recovery in a Bench Press Exercise Protocol in Moderately Physically Trained Men".	"Nutrients"/Q1	2023	The doses used were 0.3 $g \cdot kg^{-1} \cdot day^{-1}$ of creatine monohydrate for the creatine group and 0.3 $g \cdot kg^{-1} \cdot day^{-1}$ of placebo (maltodextrin) for the placebo group.	The creatine (CR) group showed a significant increase in repetitions during Sets 1 (14.8 vs. 13.6) and 2 (8 vs. 6.7) compared to the placebo (PLA) group, with no difference in Set 3. Blood lactate levels increased significantly at 10, 15, and 20 minutes post-exercise in the CR group. Additionally, mean propulsive velocity (MPV) was higher in the CR group at these points. Overall, creatine supplementation improved strength performance but resulted in greater metabolic stress and muscle fatigue during recovery.
Furtado, ETF; De Oliveira, JPL; Pereira, ISB; Veiga, EP; Da Silva, SF and De Abreu, WC	"Short term creatine loading improves strength endurance even without changing maximal strength, RPE, fatigue index, blood lactate, and mode state".	"Anais da Academia Brasileira de Ciencias"/Q2	2024	The dosing protocol for the creatine group involved a loading phase for five days, with participants receiving a total of 100 grams of micronized creatine monohydrate (20 grams per serving, spread across five pots). Additionally, they consumed 10 grams of dextrose per serving. Participants were instructed to take four servings of 7.5 grams each per day, diluted in about 400 mL of water after meals.	Creatine supplementation (20 g/day for five days) significantly improved performance in resistance exercises, specifically in the bench press. There was a 14.7% increase in the total number of repetitions and an 11.1% increase in total work compared to the placebo group, which only showed marginal increases of 1.2% and 1.4%, respectively. Creatine enhanced the ability to perform more repetitions and total work, suggesting it may increase endurance and training capacity in the bench press. Creatine also appears to contribute to better phosphocreatine regeneration and improved energy supply during exercise. Overall, the benefits of creatine include an increase in strength endurance and total work during resistance training, which could facilitate muscle mass gain.
Almeida, D; Pereira, R; Borges, EQ; Rawson, ES; Rocha, LS and Machado, M	"Creatine Supplementation Improves Physical Performance, Without Negative Effects on Health Markers, in Young Weightlifters".	"Journal of Science in Sport and Exercise"/Q2	2022	The doses used for creatine in this study involved two phases: a loading phase and a maintenance phase. Participants in the creatine group received 0.3 g/kg of body mass for 7 days (loading phase), followed by a maintenance dose of 0.03 g/kg for 21 days.	Creatine supplementation significantly improved physical performance in the creatine group compared to the placebo group. Specifically, there were notable increases in body weight and one-repetition maximum (1RM) across all evaluated exercises. Additionally, while some blood and urine health markers showed differences between groups, these variations were small and remained within clinical reference ranges. Overall, the results suggest that the dosing scheme used for creatine, in conjunction with resistance training, enhances physical performance without evident health risks for young weightlifters.
Tayebi, MM; Yousefpour, M and Ghahari, L	"Effects of creatine hydrochloride supplementation on physical performance and hormonal changes in soldiers".	"Physical Activity Review" /Q3	2021	The dose for the Cr group consisted of consuming 3 g of CrHCl mixed with 200 ml of juice, once a day, for 2 weeks. The Pl group (placebo group) consumed 3 g of dextrose in the same manner. Both supplements were premixed and distributed in resealable bags with instructions for consumption. Participants were instructed to follow the dosage without making any changes in their diet or daily activity.	Creatine hydrochloride (CrHCl) supplementation led to significant improvements in vertical jump, power performance and one-repetition maximum (1RM) in the back squat. However, CrHCl loading was not sufficient to improve 1RM in the bench press or fatigue index (FI). In addition, after 2 weeks of CrHCl supplementation, there were significant changes in testosterone and cortisol levels compared to the placebo group. The study recommends that military soldiers use CrHCl supplementation for 2 weeks to improve strength, power performance, and hormonal variables.

Authors	Titles	Source/Scimago Best Quartile	Year	Dose	Performance
Samadi, M; Askarian, A; Shirvani, H; Shamsoddini, A; Shakibaee, A; Forbes, SC and Kaviani, M	"Effects of Four Weeks of Beta-Alanine Supplementation Combined with One Week of Creatine Loading on Physical and Cognitive Performance in Military Personnel.	"International Journal of Environmental Research and Public Health"/Q2	2022	Participants were randomly assigned in two groups and instructed to take 6.4 g of beta-alanine (BA) daily for four weeks, divided into 8 capsules (3 with breakfast, 3 with lunch, and 2 with dinner). In the final week, the BA + Cr group added creatine monohydrate (Cr) at a dose of 0.3 g per kg of body weight per day, which was split into 3 portions and consumed with meals, while the BA + PL group received an isocaloric placebo of rice flour.	Mixing one week of creatine loading with four weeks of beta-alanine supplementation significantly improved vertical jump performance (indicating enhanced leg power) and increased resting testosterone levels compared to beta-alanine alone. Furthermore, the combination led to greater physical and cognitive performance improvements within the group that received both supplements. These results suggest that creatine supplementation can effectively enhance hormonal levels and physical performance, which is beneficial for military personnel facing high physical and cognitive demands.
Bernat, P; Candow, DG; Gryzb, K; Butchart, S; Schoenfeld, BJ and Bruno, P	"Effects of high-velocity resistance training and creatine supplementation in untrained healthy aging males".	"Applied Physiology, Nutrition and Metabolism"/Q1	2019	Participants supplemented with 0.1 g of creatine per kilogram of body weight per day, mixed with 0.1 g of maltodextrin per kilogram per day, while the placebo group received 0.2 g of maltodextrin per kilogram per day.	The study found significant improvements in muscle thickness, muscle strength, and some measures of peak torque and physical performance in untrained healthy aging males who participated in high-velocity resistance training (HVRT) for 8 weeks. Specifically, all measures of muscle strength showed a significant increase ($p < 0.001$), as did muscle thickness ($p < 0.001$). Some peak torque measures, such as knee flexion at 1.05 and 3.14 rad/s, also increased significantly ($p < 0.001$). Notably, there was a group × time interaction for leg press strength ($p = 0.044$) and total lower-body strength ($p = 0.039$), indicating that the creatine group experienced greater gains in leg press and total lower-body strength compared to the placebo group. Overall, HVRT combined with creatine supplementation led to enhanced strength outcomes in the participants.
Mills S.; Candow D.G.; Forbes S.C.; Neary J.P.; Ormsbee M.J. and Antonio J.	"Effects of creatine supplementation during resistance training sessions in physically active young adults".	"Nutrients"/Q1	2020	The dosage of creatine used was $0.1\ g·kg^{-1}·d^{-1}$. The creatine (Creapure® AlzChem) and the placebo (Globe® Plus 10 DE maltodextrin) were in powder form, similar in taste, color (white), texture, and appearance. Participants consumed the creatine mixed with water (900 mL), taking 50 mL of the solution containing $0.0055\ g·kg^{-1}$ of creatine or placebo immediately after each set of resistance training (18 sets per training day).	Improved muscle strength and endurance, with significant increases observed in leg press strength (Δ 43 ± 32 kg) and chest press strength (Δ 13 ± 11 kg). Males showed enhanced chest press strength over time, while the supplementation was well-tolerated with minimal adverse effects reported. Additionally, creatine reduced the fatigue index after 7 days of use, indicating better resistance to fatigue during workouts. These results highlight creatine's effectiveness in enhancing strength among physically active individuals. Additionally, creatine supplementation is associated with elevated intramuscular phosphocreatine (PCr) levels, which may facilitate faster ATP resynthesis and recovery between sets, contributing to enhanced endurance and overall performance over time.
Bogdanis G.C.; Nevill M.E.; Aphamis G.; Stavrinou P.S.; Jenkins D.G.; Giannaki C.D.; Lakomy H.K.A. and Williams C.	"Effects of Oral Creatine Supplementation on Power Output during Repeated Treadmill Sprinting".	"Nutrients"/Q1	2022	The dosage for creatine (Cr) supplementation was set at 75 mg of Cr monohydrate per kilogram of body mass per day. This dosing regimen was applied after an initial 5-day period of placebo supplementation, during which participants received 75 mg of glucose per kilogram of body mass per day.	Cr supplementation significantly improved sprint endurance and total work output during repeated 10-second sprints, as evidenced by increased mean power output (MPO) and running speed in the latter part of the exercise session. Importantly, while aerobic contributions to energy supply, indicated by VO2 levels, remained unchanged, Cr supplementation led to a notable 20.1% reduction in plasma ammonia levels post-exercise. This reduction suggests enhanced ATP turnover and less metabolic stress, likely due to an increased reliance on phosphocreatine (PCr) for energy production. Overall, the study highlights that creatine not only boosts performance in weight-bearing activities but also facilitates faster recovery during repeated sprints by optimizing energy availability and reducing metabolic byproducts associated with fatigue.

Note. The information in this table has been collected and synthesized from the key findings of nine scientific articles. It is used solely for the purpose of conducting a literature review, respecting copyright and properly acknowledging the original sources. This synthesis is not intended to plagiarize, but to contribute to scientific knowledge through comparative analysis and discussion.

RESULTS

Table 1 summarizes the key reviewed studies, providing an overview of the creatine doses used and the observed effects on physical performance. Through this table, the most relevant conclusions from each investigation are highlighted, facilitating a direct comparison between different approaches and obtained results.

DISCUSSION

Creatine supplementation has been the subject of numerous studies evaluating its impact on physical performance, especially in high-intensity activities. The results shown in the "*performance*" column of the document consistently demonstrate that creatine administration, across various doses and protocols, generates significant improvements in subjects' ability to perform strength and endurance exercises. These findings are mainly related to the role of phosphocreatine in the rapid regeneration of ATP, the primary energy source for muscle contraction during high-demand exercises.

One of the main benefits observed is creatine's ability to improve performance under fatigue conditions. In young soccer players, 14 days of supplementation at a dose of 0.3 g/kg/day resulted in a significant increase in muscle power, allowing participants to maintain their ability to generate force despite intra-session fatigue. This outcome is attributable to higher phosphocreatine saturation in the muscles, which facilitates faster ATP regeneration and, consequently, better response in repetitive high-intensity activities.

Furthermore, in resistance exercises such as bench presses, creatine supplementation not only increased muscle strength, but also allowed for a greater number of repetitions and an increase in total work performed. In one specific study, participants supplemented with creatine showed a 14.7% increase in the number of repetitions and 11.1% increase in total work performed compared to a placebo group. This finding highlights the role of creatine not only in improving maximal strength, but also in maintaining repetitive efforts, which is crucial in sports and training that require multiple high intensity sets.

Creatine has also been shown to be effective in improving recovery parameters between sets, significantly decreasing fatigue levels. For example, in repeated treadmill sprints, creatine supplementation improved both endurance and recovery speed between efforts. This effect was observed along with a 20.1% reduction in plasma ammonia levels, suggesting a reduced accumulation of metabolic by products associated with fatigue, thus improving energy regeneration capacity.

At last, it is important to emphasize that creatine supplementation not only affects strength and endurance, but also positively influences body composition and VO2 max, as was observed in youth wrestlers. Combining strength training with creatine supplementation resulted in significant increases in muscle mass and VO2 max, indicating improvements in aerobic capacity. These results highlight the versatility of creatine as a supplement for both strength and endurance sports.

CONCLUSION

The studies analysed showed that creatine supplementation has positive and consistent effects on physical performance, especially in high-intensity and repetitive activities. The underlying mechanisms of these benefits are related to the increase in intramuscular phosphocreatine saturation, allowing a faster regeneration of ATP, which facilitates a better muscular response in exercises involving fast and explosive movements. In addition, creatine has shown a significant ability to reduce metabolic fatigue levels, improve muscular endurance and accelerate recovery between complex sets, which is essential in sports and training that require high energy expenditure. The benefits of creatine are not limited to anaerobic performance but also extend to improvements in aerobic capacity and body composition, with observed increases in VO2 max and muscle mass. These metabolic and physiological adaptations position creatine as a key ergogenic supplement, not only for high-performance athletes, but also for more general populations seeking to optimize their physical capacity in endurance and strength exercises. Current evidence strongly supports the use of creatine as an effective and safe agent for enhancing both performance and recovery in a variety of athletic contexts.

AUTHOR CONTRIBUTIONS

Conceptualization, Zevallos-Aquije, Axel.; methodology, Zevallos-Aquije, Anneliese and Zevallos-Aquije, Axel; software, Zevallos-Aquije, Axel; validation, Salas-Bolaños, Rosa Alejandra; formal analysis, Maravi-Cardenas, Alvaro Jose; investigation, Zevallos-Aquije, Axel; resources, Zevallos-Aquije, Axel; data curation, Palomino-Salcedo, Karen; writing—original draft preparation, Zevallos-Aquije, Anneliese; writing—review and editing, Salas-Bolaños, Rosa Alejandra; visualization, Maravi-Cardenas, Alvaro Jose; supervision, Salas-Bolaños, Rosa Alejandra; project administration, Palomino-Salcedo, Karen. All authors have read and agreed to the published version of the manuscript.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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REVIEW ARTICLE

Creatine beyond muscle metabolism: Changing constant of human body

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ABSTRACT

Creatine plays a vital role in the normal metabolism of the central nervous system, heart, bones, and muscle tissues. It is one of the most extensively used dietary supplements worldwide. Creatine plays a critical role in energy metabolism, functioning as a source of high-energy phosphate groups that facilitate the fast recycling of ADP into ATP within cells, particularly during stressed states. The biosynthesis of creatine requires the essential substrates arginine and S-adenosylmethionine, which can influence the regulation of metabolism in the human body. Creatine acts as a negative regulator of its own synthesis and transport. The daily creatine dose can reach 0.4 g/kg of body weight. Although the absorption rate of high doses of creatine is 20-40%, they help enhance physical performance and athletic results. Despite the long history of creatine research and widespread use of creatine in sports, the precise molecular mechanisms governing its metabolism, excretion, and the functioning of the phosphocreatine energy buffer remain to be studied in detail. This review analyses the recent research on the impact of creatine supplements on health and athletic performance and the molecular mechanisms of its regulation within the human body.
Keywords: Creatine metabolism regulation, Human health, Physical performance, Creatinine clearance.

Cite this article as:
Boretsky, Y., Hlozhyk, I., Hashchyshyn, V., Paraniak, N., Tymochko-Voloshyn, R., Ivashchenko, V., Boretsky, V., & Svyshch, Y. (2025). Creatine beyond muscle metabolism: Changing constant of human body. *Journal of Human Sport and Exercise, 20*(2), 715-730. https://doi.org/10.55860/jynq3v03

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Submitted for publication January 29, 2025.
Accepted for publication March 07, 2025.
Published March 26, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/jynq3v03

INTRODUCTION

Creatine (after the Greek word for meat, κρέας "*kreas*", methylguanidoacetic acid, $(H_2N)(HN)CN(CH_3)CH_2CO_2H$) was originally isolated by Chevreul from skeletal muscles in 1832. The majority of creatine (about 90%) in the human body is accumulated in skeletal muscles, where the total concentration of creatine and phosphocreatine can reach up to 30 mM. In brain tissue, the content of creatine is significantly lower (up to 10mM) (Walliman et al., 1992; Wyss et al., 2007). The body's creatine reserves are maintained in two ways: by endogenous biosynthesis and through dietary intake (Bonilla et al., 2021; Wallimann & Harris, 2016; Wyss & Schulze, 2002; Wyss et al., 2007).

Creatine stimulates various physiological responses beyond its contribution to cellular energy needs. It promotes the differentiation of muscle cells and neurons and protects them from oxidative stress (Sestili et al., 2016; Wallimann et al., 2011). Mutations in the genes encoding the enzyme of creatine biosynthesis and/or its transporter cause psycho-neurological disorders that compromise speaking ability and motor skills. These results further indicate the importance of creatine in human health (Cheillan et al., 2012). In healthy individuals, creatine intake improves the time to react to choices and psychological balance and reduces mental fatigue (Candow et al., 2023; Watanabe et al., 2002). Creatine dietary supplements support normal heart function and bone tissue mineralization (Balestrino, 2021; Forbes et al., 2022).

In most cases, using creatine dietary supplements provides increased anaerobic buffering capacity and reduces protein breakdown, resulting in increased muscle mass and physical performance (Twycross-Lewis et al., 2016). Consuming large amounts of creatine in doses higher than recommended can cause nausea, vomiting, diarrhoea, and acne. These adverse effects disappear quickly after properly adjusting creatine consumption (Ostojic & Ahmetovic, 2008). If the recommended doses are exceeded, most of the creatine consumed is excreted from the body within a day. The mechanisms and regulation of creatine excretion require further study.

Creatine and its phosphorylated form are relatively unstable and degrade to creatinine at a rate of about 2% per day (Wyss & Kaddurah-Daouk, 2000). Creatinine is excreted from the body by the kidneys through organic ion transporters. The levels of creatinine in blood serum and urine depend on many factors. Despite that, the average amount of creatine and creatinine in the body is relatively constant for each individual (Chernozub et al., 2020). In several studies, this indicator has been used to evaluate the content of other marker compounds in the body (Hall & Trojian, 2013; Oosterwijk, 2022).

Creatine is one of the most widely used ergogenic aids for athletes (Bonilla et al., 2021; Harris et al., 1992). Creatine is also increasingly used as a dietary supplement by other population groups, significantly increasing its production and sales (Bredahl et al., 2021). The purpose of this review is to provide an up-to-date summary and discussion of the current body of research focusing on: (1) the regulation of creatine metabolism, (2) the role of creatine in human health, (3) use of creatine as a dietary and bioactive supplement.

METHODS

This review was completed using a narrative, non-systematic approach. The search for papers was conducted using the following databases: PubMed, Cochrane, ScienceDirect, EBSCO-host from 2000 to 2024. The search was performed using the following keywords and their combinations: creatine, creatine biosynthesis regulation, creatine transport, creatine supplementation, human health, sport performance, resistance training, muscle damage, training adaptation, creatinine clearance. Articles were chosen for inclusion based on the information they outlined and with a specific focus on creatine biosynthesis regulation, creatine transport, creatine supplementation, human health. Further citations were found, evaluated, and incorporated. Thus, in some instances, several articles beyond the period mentioned above were included.

DISCUSSION

Creatine biosynthesis and transport

The first reaction in creatine biosynthesis, the transfer of the amidino group of L-arginine to the N-amine group of L-glycine, is catalysed by L-arginine-glycine amidinotransferase (AGAT) (EC 2.1.4.1) (Tormanen, 1990; McGuire et al., 1984). This is the rate-limiting step in this biosynthetic pathway. In this reaction, L-arginine formed within the kidney is used as a donor of the amidino group (Wyss, 2000). Although arginine is formed de novo in humans, these synthetic pathways do not provide sufficient arginine quantities. Thus, humans do have dietary needs of it. It should be noted that arginine serves not only as a building block of proteins but also as an essential substrate for the synthesis of nitric oxide, an effector of MTOR and focal adhesion kinase cell signalling pathways. Lack of arginine can compromise immunity, anti-oxidative responses, wound healing etc. The products of the first reaction in creatine biosynthesis are L-ornithine and guanidinoacetate. It is believed that in the human body, most guanidinoacetate is synthesized in the kidneys. Two forms of L-arginine: glycine amidinotransferase have been identified in kidney cells: cytosolic and mitochondrial, both encoded by the GATM gene (Humm et al., 1997). N-guanidinoacetate is transported through the blood to the liver, where it is methylated. S-adenosylmethionine (SAM) is used as the methyl group donor. About 40% of S-adenosylmethionine synthesized is thought to be spent on creatine biosynthesis (Brosnan et al., 2011). The synthesis of S-adenosylmethionine, the transfer of the adenosyl group from ATP to methionine, is catalysed by methionine adenosyltransferase (EC 2.5.1.6). Methionine adenosyltransferase exists in three forms that differ by subunit composition (mains are encoded by the human genes MAT1A and MAT2A), tissue expression and kinetic properties (Chamberlin et al., 2000). It is hard to overstate the importance of S-adenosylmethionine balance for human metabolism. This compound is used as the sole source of the methyl group in most methylation reactions, including creatine biosynthesis, whereas its metabolites, S-adenosylhomocysteine and homocysteine, can provoke various diseases. The methyl group from S-adenosylmethionine is transferred to guanidinoacetate at the final step of creatine biosynthesis, catalysed by guanidinoacetate-N-methyltransferase (GAMT) (EC 2.1.1.2) (Joncquel-Chevalier Curt et al., 2015). Thus, the biosynthesis of creatine requires two potentially deficient substrates, arginine and S-adenosylmethionine, whereas a decrease in their content can influence the regulation of human body metabolism. Someone could speculate that substantial amounts of both arginine and S-adenosylmethionine are stored for cellular needs under creatine supplementation conditions.

Synthesized creatine is distributed through the blood to body tissues and absorbed according to their needs. The creatine absorption is facilitated by a high-affinity transporter CRT-1 (gene SLC6A8). The properties of this transporter have been well studied and described in numerous works and reviews (Ferrada et al., 2024; Salomons et al., 2003, Tropak et al., 2023). The human SLC6A12 gene encodes another potential creatine transporter. A mutation in this gene, found in patients with cataracts, significantly reduces creatine transport. In rats lacking the SLC6A12 homolog, elevated creatine concentrations have been observed in urine (Abplanalp et al., 2013). Possibly, the potential creatine transporter encoded by the SLC6A12 gene is not expressed in the cells of the central nervous system (Bhatt et al., 2023). This is indirectly supported by studies on the role of the main creatine transporter (CRT-1) and mutations in its gene SLC6A8 that cause psycho-neurological disorders (Ferrada et al., 2024). The involvement of both transporters in the excretion of creatine and creatinine should be investigated, especially in persons who use creatine dietary supplements.

Although creatine biosynthesis in homeothermic species has been explored for a long time, questions regarding the regulation of this pathway, the involvement of different cells and tissues in its synthesis, and their ability to transport creatine have to be studied in detail (Barcelos et al., 2016; Carducci et al., 2012; Yan & Bu, 2024).

Phosphocreatine as an energy buffer

The involvement of phosphocreatine in energy metabolism has been extensively studied using muscle cells as a model. During the initial seconds of physical exertion, when the level of ADP in myocytes rises significantly, phosphocreatine is used for fast regeneration of ATP (Bessman & Carpenter, 1985; Wallimann & Harris, 2016). The transfer of phosphate groups from phosphocreatine to ADP is catalysed by creatine kinase present in myofibrils (MM-CK) (Bessman & Carpenter, 1985; Guimarães-Ferreira, 2014; Zhao et al., 2007). The products of this reaction are creatine and ATP, which is used again as an energy source for muscle contraction. Creatine and orthophosphate formed in the myofibrils diffuse back to the mitochondria. In mitochondria, the ATP level is very high, whereas the levels of phosphocreatine and ADP are low. This balance favours the phosphorylation of creatine using the energy from ATP. The reaction is catalysed by creatine kinases located in the mitochondrial intermembrane space (Bonilla et al., 2021; Echegaray & Rivera, 2001; Qin et al., 1999; Wallimann & Harris, 2016). It should be noted that one of them, namely umtCK creatine kinase, interacts with the inner membrane ATP transporter and the outer membrane anion transporter VDAC (voltage-dependent anion carrier), facilitating the rapid transfer of phosphocreatine from the mitochondria to the cytosol (Wallimann & Harris, 2016).

The products of this reaction are phosphorylated creatine and ADP. The formed phosphocreatine diffuses back from mitochondria to myofibrils, where ADP is phosphorylated to ATP again. Thus, mitochondrial aerobic metabolism is the primary source of energy that is transferred to creatine by means of phosphorylation. Then, this high-energy phosphate group is transferred on ADP, rapidly restoring ATP concentration in the myofibrils. This energy supply mechanism, known as the "*phosphocreatine shuttle*" serves as an effective "*energy buffer*" for muscle tissue (Bessman & Carpenter, 1985; Bonilla et al., 2021; Miotto & Holloway, 2016; Wallimann & Harris, 2016).

A plausible explanation for such a complex transfer of high-energy bonds is that the phosphocreatine molecule is significantly smaller and diffuses faster than the relatively large ATP molecule (Balestrino, 2021). This ensures the relative stability of ATP concentration, which is the most essential and indispensable effector of the regulation of metabolisms. The capacity and efficiency of this energy supply mechanism depend on the creatine concentration in muscles, the intensity of mitochondrial aerobic metabolism (oxidative phosphorylation), and the balance of creatine kinases activity. Similar mechanisms have been found to operate in the cells of the nervous and immune systems (Saito et al., 2022; Schlattner et al., 2016).

Four creatine kinase genes have been identified in the human genome. The CKMT1B gene, encoding mitochondrial (ubiquitous) creatine kinase umtCK, is located on chromosome 15 (15q15.3) in the sequence with coordinates 15:43300001-44500000. The CKMT2 gene, encoding muscle sarcomeric mitochondrial creatine kinase smtCK, is located on chromosome 5 (5q14.1) in the sequence with coordinates 5:81201341-81301565. The CKM gene, encoding muscle cytosolic creatine kinase CK-MM, is located on chromosome 19 (19q13.32) in the sequence with coordinates 45306413-45322875. The CKB gene, encoding brain cytosolic creatine kinase BB-CK, is located on chromosome 14 (14q32.33) in the sequence with coordinates 14:103519667-103522833 (https://www.ebi.ac.uk/gwas/genes/CKB). Several nucleotide substitutions (polymorphisms) were identified in the human genes encoding creatine kinases. Some of them are very rare (frequency less than 0.5%), which may indicate their impact in the development of pathologies (https://www.ebi.ac.uk/gwas/). A search for information in the PubMed database revealed contradictory results regarding the impact of creatine kinase gene polymorphisms on the development of motor skills (Chen et al., 2017; Echegaray & Rivera, 2001; Ginevičienė et al., 2021). More data are required to verify such possible influence of the genetic background.

Regulation of creatine metabolism

Using human haploid cells (HAP1) as a model, it was found that the amount of AGAT protein fused with a reporter protein is regulated in response to creatine concentrations in the incubation medium. Authors speculated that there is a specific mechanism of creatine-dependent transcriptional regulation of this pathway, as proposed in the rat model (McGuire et al., 1984; Tropak et al., 2023). Similar patterns have been observed in studies of the mouse brain: a decrease in creatine availability caused an increase in the expression of the creatine transporter gene (Jensen et al., 2020). Based on the comparative analysis of these studies, one can suggest that in homeothermic species, the expression of genes involved in creatine biosynthesis and transport increases significantly during creatine deficiency. Thus, creatine is a negative effector of its own biosynthesis and transport. Most likely, this mechanism is of particular importance for the proper balance of S-adenosylmethionine and arginine, the key substances in the metabolism of methyl groups and nitric oxide, respectively.

Interestingly, the use of creatine precursor guanidinoacetate as a dietary supplement caused a significant increase in creatine concentration in the blood of healthy individuals (Ostojic et al., 2013; Ostojic, 2022; Schulze, 2003; Stockler-Ipsiroglu & van Karnebeek, 2014). These findings indirectly suggest that guanidinoacetate may be involved in mechanisms activating the second reaction of creatine synthesis. Possibly such a mechanism evolved evolutionary to avoid cytotoxicity of guanidinoacetate. In addition, the activity of the creatine transporter is regulated by AMP-activated protein kinase via the mTOR pathway, reflecting a possible influence on energy metabolism (Li et al., 2010). Although these hypotheses can explain the substantial impact of exogenous creatine on physical performance, they must be studied in detail.

At least two types of post-translational modifications were reported to regulate the activity of muscle cytosolic creatine kinase (M-CK), namely modifications of a cysteine residue and phosphorylation. M-CK loses enzymatic activity when a cysteine residue (Cys283) is chemically modified or when an intermolecular disulfide bond is formed (Hurne et al., 2000; Montasell et al., 2022). Additionally, the oxidized form of the enzyme cannot interact with myomesin, a protein of the M-line in the sarcomere. The formation of a disulfide bond between two subunits (oxidized form of the enzyme - O-CK) leads to reduced enzyme stability. Unlike the reduced form (R-CK), the oxidized form of the enzyme undergoes rapid degradation (Peris-Moreno et al., 2020; Zhao et al., 2007). Thus, the oxidation of this creatine kinase blocks the utilization of creatine phosphate for rapid ATP resynthesis in myofibrils.

Using hibernating animals as a model it was found that non-phosphorylated muscle creatine kinase exhibits higher activity than the phosphorylated form of the enzyme (Abnous & Storey, 2007). A similar regulatory mechanism was reported in the cardiac muscle of rats, where M-CK is phosphorylated by protein kinase C. Phosphorylation of M-CK shifts the equilibrium of the reaction toward the synthesis of creatine phosphate. In contrast, dephosphorylation of the enzyme shifts the equilibrium of the reaction toward the resynthesis of ATP from ADP (Lin et al., 2009). The obtained results indirectly suggest that the respiratory activity of the tissue, i.e. ATP/ADP/AMP ratio may influence the mechanisms of ATP resynthesis by regulating the activity of creatine kinases (Peris-Moreno et al., 2020; Reddy et al., 2000). Nevertheless, phosphocreatine decreases the sensitivity of mitochondrial respiration to ADP, whereas creatine has the opposite effect. During transition from rest to high intensity exercise, decrease in the phosphocreatine/creatine ratio will effectively increase the sensitivity of mitochondrial respiration to ADP (Walsh et al., 2001). One can suggest that there could be mutual interdependence between ATP/ADP and phosphocreatine/creatine ratios that could serve as an additional mechanism of fast respiration regulation in tight accordance to organisms needs. Obviously, this hypothesis provides some sufficient details to our understanding of molecular basis of a proper regulation of respiration, but it has to be verified experimentally.

Thus, various mechanisms are involved in regulating creatine phosphate metabolism, responding to the concentration of creatine in cells, the cell's current energy needs, and respiratory activity. Although most experiments were done on animal models, it can be assumed that very similar mechanisms of regulation of creatine metabolism function in the human body.

Using creatine to enhance sports performance

Creatine supplementation is one of the most efficient and useful ergogenic aids for athletes, which has been used since the early twentieth century. Its production and use both rose dramatically during the last decade of the twentieth century (Harris et al., 1992). Endogenous synthesis of creatine provides about half of the daily needs (Brosnan & Brosnan, 2016). The remaining part of the necessary creatine is obtained from animal-derived food products. Vegetarians who have creatine levels in tissues lower by 20–30% are recommended to consume 2–3g/day of creatine to maintain its physiological level (Kreider & Stout, 2021).

Results of molecular genetic studies of psycho-neurological disorders caused by creatine deficiency emphasize the importance of creatine metabolism for human health. Inherited creatine deficiency compromises speaking ability and motor skills and can cause progressive epilepsy and/or autism spectrum disorders (Cheillan et al., 2012). These disorders are caused by mutations in human genes involved in creatine biosynthesis or transport (Cheillan et al., 2012; Haghighatfard et al., 2023). Creatine supplementation (8g/day for 5days) increases oxygen consumption in the brain and reduces mental fatigue during repetitive mathematical calculations in healthy individuals (Watanabe, 2002). Administration of significantly higher doses (20g/day for 7days) improves time to react to choices and psychological balance (McMorris et al., 2006). Therefore, creatine supplementation positively affects the central nervous system, particularly under conditions of fatigue (Candow et al., 2023).

The creatine metabolism is essential for the normal functioning of the heart. Apparently, the phosphocreatine "*energy shuttle*" is extremely important for the proper functioning of the myocardium. It is suggested that healthy subjects will benefit from creatine supplementation, but such benefit could not be confirmed by in vivo human heart studies (Balestrino, 2021). During heart failure, levels of both creatine and phosphocreatine in cardiomyocytes decrease. It can be speculated that phosphocreatine is better retained by cardiomyocytes than creatine, as observed for the glucose-phosphoglucose pair in hepatic cells. This suggestion remains to be checked experimentally.

There are some contradictions in published data concerning the impact of creatine supplementation on the mineralization and metabolism of bone tissue (Forbes et al., 2018; Forbes et al., 2022). Possibly the reason for such inconsistency is differences in doses and approaches of creatine supplementation. In addition, it has been found that doses of creatine and the method of its consumption are important factors influencing the metabolism of bone cells – osteoblasts and osteoclasts (Zhu et al., 2023). In cell culture models, adding creatine to the cultural medium has been shown to enhance metabolic activity and differentiation of osteoblasts (Gerber et al., 2005). However, it was suggested that activation of the phosphocreatine energy buffer in osteoclasts led to an activation of bone tissue resorption processes (Zhu et al., 2023). The results of these studies indicate that creatine metabolism and the functioning of the phosphocreatine energy buffer are both essential for bone tissue synthesis and resorption (Forbes et al., 2022; Gerber et al., 2005; Zhu et al., 2023).

Creatine is recommended as an ergogenic aid in strength sports and for athletes who endure regular maximal loads (e.g., American football, soccer, basketball, tennis, etc.) (Kreider et al., 2017). In addition to its positive impact on physical performance, creatine supplementations improve psychological balance and time to react to choice (McMorris et al., 2006). In most cases, using creatine as a dietary supplement leads to an increase in energy buffer capacity and muscle mass growth that results in enhanced physical performance (Twycross-Lewis et al., 2016). However, in some studies, no positive effect of creatine supplements on physical performance was observed (Armentano et al., 2007). This inconsistency may be explained by individual differences in the maximal creatine contents in the body (Hall & Trojian, 2013). In approximately 30 % of individuals, primarily those with creatine levels close to 150 mmol/kg of dry muscle, creatine supplements proved ineffective or only slightly effective. At the same time, in individuals with an initial creatine content of less than 110 mmol/kg of dry muscle, significant performance increases were observed with creatine supplementation (Greenhaff et al., 1993; Harris et al., 1992).

The mechanisms of the positive effects of exogenous creatine are not understood well. The observed ergogenic effects could be explained by an increased content both of in creatine and its phosphorylated form in muscles or by a decrease content of AMP breakdown products in muscles. According to this hypothesis, the primary role of phosphocreatine is to prevent the accumulation of ADP and AMP, as well as their metabolic products, inosine monophosphate and hypoxanthine. In favour of this hypothesis, creatine dependent reduction of muscle inosine monophosphate content was observed (McConell et al., 2005). Later it was reported that creatine supplementation causes decrease of hypoxanthine and uric acid in plasma (Tang et al., 2014). Creatine also can stimulate the healing of muscular microtears caused by physical loads, thereby improving muscle growth and maintenance (Bredahl et al., 2021; Hashchyshyn et al., 2022). It is important to note that high dosages of exogenous creatine can completely block its biosynthesis in the human body (Peters et al., 2015). Thus, creatine supplementation could improve the balance of arginine and S-adenosylmethionine, which is currently used as an antidepressant. The impact of these mechanisms on the overall ergogenic effect of creatine has to be studied in detail.

Table 1. Creatine supplementation recommended in different sports.

№	Dosage/Duration	Sport activity	Citation
1.	30 g/day X 7 days	Soccer	Ostojic, 2004.
2.	20-30g/day X 6-7 days + 5g/day X 63 days	Soccer	Mielgo-Ayuso et al., 2019.
3.	(~20 g/day) 0.3 g/kg of body weight X 6 days + ~2 g/day X 28 days	Tennis	Pluim et al., 2006.
4.	(~30 g/day) 0.35 g/kg of body weight X 7 days	Sprint running	Delecluse et al., 2003.
5.	20 g/day X 1-4 days 10 g/day X 5-6 days 5 g/day X 7-28 days	Volleyball	Lamontagne-Lacasse et al., 2011.
6.	(~3 g/day) 0.04 g/kg of body weight X 70 days	Rowing	Fernández-Landa et al., 2020.
7.	(~20 g/day) 0.3 g/kg of body weight X 5 days	Ice-hockey	Cornish et al., 2006.
8	~5 g/day 0.3 g/ X 4 days	Swimming	Theodorou et al., 2005.
9.	4 g/day X 42 days	Taekwondo	Manjarrez-Montes de Oca et al., 2013.
10.	20 g/day X 5-7 days	Weightlifting Powerlifting	Kreider, 2003.

Based on the studies by Harris et al. (1992), it was recommended to take 20 grams of creatine monohydrate per day for 5-10 days, achieving a 25-30% increase in muscle creatine levels. Table 1 presents several different approaches, but there are many more protocols for creatine supplementation (Wax et al., 2021). Depending on the type of sport, consuming 3-30 grams per day of creatine as supplements to sports cocktails is recommended. Plasma concentration of creatine typically reaches its maximum approximately 60 minutes after oral ingestion of creatine monohydrate (Hultman et al., 1996; Kreider et al., 2017). After muscles creatine stores are fully saturated, it is recommended to consume 3-5 grams of creatine per day to keep them. However, some studies suggest that in some instances, dosages of 5-10 grams per day may be necessary (Hall & Trojian, 2013; Harris et al., 1992; Hultman et al., 1996; Greenhaff et al., 1994; Kreider, 2003). The alternative dosing protocol involves taking 3 grams per day of creatine monohydrate over 28 days (Hultman et al., 1996).

The use of the metabolic precursor of creatine, guanidinoacetic acid, to increase creatine levels in the body was reported earlier. It was found that oral administration of guanidino acetic acid is an effective aid to increase creatine content in muscles (Ostojic, 2022; Ostojic et al., 2013; Schulze, 2003; Stockler-Ipsiroglu & van Karnebeek, 2014). Obtained results could indicate a possible role of guanidinoacetic acid as a positive effector of creatine biosynthesis. However, this approach may cause severe issues due to the toxicity of guanidinoacetic acid and increased homocysteine levels in plasma. The latter is a risk factor in cardiovascular disease development (Peters et al., 2015). Disturbance of methyl group transfer and elevated homocysteine levels are thought to be both a cause and a consequence of metabolic syndrome (Ulloque-Badaracco et al., 2023). That can lead to disturbances in eating behaviour and changes in the human microbiome, resulting in decreased performance and athletic achievement (Lind et al., 2018; Radziejewska et al., 2020). So, such an approach is not currently recommended.

While creatine is a relatively safe supplement, it can cause a few adverse effects when overdosed. The most common side effect is temporary weight gain due to water retention. It is known that creatine causes moderate water retention and reduces diuresis, especially during the loading phase. Increased intracellular water volume increases the risk of developing compartment syndrome and muscle spasms (Butts et al., 2018; Kim et al., 2015). Creatine supplementations also could lead to both liver and kidney function disturbances. Other digestive tract disturbances, such as nausea, vomiting, diarrhoea, and acne, may occur (Ostojic & Ahmetovic, 2008). To reduce these, it is recommended to fortify creatine-containing sports cocktails with optimal proportions of vitamins B6, B9, B12, and betaine (Selhub, 1999; Ulloque-Badaracco et al., 2023). Adverse effects caused by creatine overdose quickly disappear after creatine consumption is appropriately reduced.

In most cases, using recommended creatine supplements significantly increases its content in muscles. However, simple calculations based on published data indicate that the absorption rate is less than 40%, whereas experimental data suggest that about half of the consumed creatine is excreted in urine within 24 hours (Burke et al., 2001). It is possible that creatine could diffuse into the intestines, where it might degrade under the influence of the gut microbiota (Wyss & Kaddurah-Daouk, 2000).

Excretion of creatinine from the body

Creatine and its phosphorylated form are somewhat unstable. They irreversibly degrade to creatinine. The degradation rate is approximately 2% per day (Wyss & Kaddurah-Daouk, 2000). Apparently, creatinine has no biological function and is excreted by the kidneys. Organic cation transporter (OCT2) had been shown to play a key role in the active excretion of creatinine (Ciarimboli et al., 2012; Lepist et al., 2014; Shen et al., 2015). Recently, it was suggested that some other transporters (namely organic anion transporter (OAT2), multidrug and toxin extrusion pump (MATE1/2K)) could also be involved in creatinine extrusion (Mathialagan et al., 2024; Mathialagan et al., 2021). One can assume that these transporters are involved in creatine excretion, too. That can explain the high excretion of creatine into the urine when creatine monohydrate is used as a supplement. Besides, creatinine can diffuse into the intestines, where it could undergo further degradation by bacterial enzymes (Zakalskiy et al., 2020; Wyss & Kaddurah-Daouk, 2000).

The creatinine concentration in plasma is used in routine medical practice to determine the glomerular filtration rate, an integral indicator of a kidney excretory function. The normal creatinine levels in blood for women is 44-97μM, whereas for men – 62-115μM. Decreased creatinine concentration is observed with insufficient meat consumption (for instance, vegetarian diets, fasting) and during the first and second trimesters of pregnancy. Hypercreatininemia can be associated with kidney pathology, including conditions caused by medications (such as contrast agents for X-rays, aminoglycoside antibiotics, cephalosporin antibiotics, statins, etc.). When only one kidney is functioning, the creatinine level in blood typically increases to 159-168μM. Elevated serum creatinine concentration (above 177μM and 885μM for children and adults correspondingly) indicates renal insufficiency (Banfi et al., 2012). Dehydration, muscle damage, and consumption of large amounts of creatine as a dietary supplement can cause significantly increased creatinine content in blood and urine (Samra & Abcar, 2012).

In healthy individuals, the levels of creatinine in serum and urine are characteristic indicators for each person, depending on total muscle mass, fitness level, individual genetic traits, daily water intake, etc. (Chernozub et al., 2020; Karakukcu, 2024; Oosterwijk, 2022). This observation allows for assessing adaptive changes in training processes and the detailed analysis of changes in other biochemical markers during adaptation to physical exertion.

CONCLUSIONS

Creatine is a widely used ergogenic aid among athletes. In most cases, it has been shown that supplementing with creatine can significantly improve an individual's ability to adapt to intense physical exertion and enhance athletic performance. The effectiveness of creatine supplementation can vary considerably among individuals, and this variation can be attributed to individual genetic characteristics. These characteristics determine the efficiency of creatine absorption and accumulation. Understanding these genetic factors is crucial because it can help explain why creatine supplementation is more effective for some individuals than others. The role of the potential creatine transporter SLC6A12 in the processes of its absorption and excretion requires further investigation. The inconsistent results of recent studies on the impact of creatine kinases genes polymorphisms on the development and manifestation of motor skills illustrate the complexity of the subject and underline the need for further investigation. Consuming excessive amounts of creatine can suppress its own biosynthesis, increasing the levels of arginine and S-adenosylmethionine, with concomitant positive physiological effects. Creatine is regarded as one of the positive effectors in the regulation of myoblast proliferation and differentiation. The importance of these effects of creatine in adaption to physical load requires further investigation. However, it should be noted that the type and frequency of physical exertion affect the level of creatine accumulation. Possibly, there is a close interrelationship between the regulation of the phosphocreatine buffer's functioning and the intensity of respiration. Future studies may provide insight into the mechanisms that regulate creatine homeostasis in the human body.

AUTHOR CONTRIBUTIONS

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SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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REVIEW ARTICLE

The effect of an educational program using artificial intelligence applications on learning backstroke skills among people with motor disabilities

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ABSTRACT

Purpose, this study aimed to identify the impact of an educational program using artificial intelligence applications on learning backstroke skills among people with motor disabilities, Methods, the study sample consisted of (22) students with motor disabilities at Hashemite University and registered for the second semester of the academic year 2024/2025 (who are not fluent in swimming skills). They were divided into two groups, an experimental group (12) students and a control group (10) student. The researcher used the experimental method by designing the experimental and control group for its suitability and objectives of the study. An educational program in swimming using artificial intelligence applications was applied to the experimental group for 8 weeks three times a week and 45 minutes each unit, while the control group was taught in the traditional way, Results, the results of the study indicated that there are statistically significant differences between the pre- and post-measurements and in favour of the post-measurement in the skill level of the two groups. Conclusion, the researcher recommends adopting the proposed educational swimming program for basic skills in swimming using artificial intelligence applications.
Keywords: Artificial intelligence, People with mobility disabilities, Swimming, Educational program.

Cite this article as:
Al Qawasmeh, K. T., Alhamad, A. M. H., Alshorman, S. A., Alghodran, S. M., & Abu Eid, F. S. (2025). The effect of an educational program using artificial intelligence applications on learning backstroke skills among people with motor disabilities. *Journal of Human Sport and Exercise, 20*(2), 731-741. https://doi.org/10.55860/z7882d33

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Submitted for publication February 05, 2025.
Accepted for publication March 14, 2025.
Published March 26, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/z7882d33

INTRODUCTION

Scientific innovations and modern technologies are considered one of the hallmarks of the twenty-first century and it is difficult to abandon them because of their prominent role in achieving the best results in the world, which all countries seek to own and apply to reach the podiums in sports forums, where technology has become a reality that we cannot ignore (Hussein, 2021).

Since ancient times, man has contributed to the creation of machines and devices that facilitate the requirements of his diverse life, and employed them in the fields of health, agricultural, industrial, educational, and other fields, and the machine has become an integral part of the life of modern man (Melaw et al, 2020).

Howard (2019) believes that artificial intelligence is one of the modern technological applications that can be used in multiple academic aspects such as worksheets, performance evaluation, assignments, correction of errors, various tests, and others, which facilitates and simplifies education by presenting educational content and explaining it in a fun way and an interesting presentation that accompanies sound, image and simulates reality. Where the educational sector has been significantly affected by the changes and transformations of society, which requires workers in the university sector to keep pace with this development to survive and reach the highest levels, whether at the local, regional, or international levels.

Among the uses of artificial intelligence in the educational field is that it contributes to identifying the capabilities of students and designing study programs that suit the individual abilities and different needs of students, as well as contributing to the creation of digital learning interfaces and simplifying concepts, in addition to helping the trainee to keep pace with educational lessons at multiple times and outside official working hours, which contributed to improving the academic level of students (Chen et al, 2020).

Abu Arida (2021) indicates that the use of artificial intelligence applications in teaching motivates students, improves the learning process, and increases the efficiency of the teaching process by deviating from the routine pattern adopted in teaching, which may sometimes boring students.

Artificial intelligence as seen by (Zhuo, 2021) are programmed computer applications that have certain characteristics that simulate human mental abilities and work patterns, and among these characteristics they help to learn and deduce.

Ismail (2021), Taweel and Noureddine (2023) stated that the use of artificial intelligence has become an imperative necessity to develop the sports field, whether in sports facilities or training camps, correct common errors of skills, audit arbitration cases, or process various data to develop sports performance. It also contributes to the creation of a virtual reality database that is used to improve and improve the skill performance of various sports.

This is confirmed by (Robert et al, 2016) and Essam and Ayyad (2021), as many artificial intelligence applications that are used in the sports field simulate the reality of sports, and audio-visual videos related to artificial intelligence help the coach by storing and analysing the data that is recorded during play to know the performance of the players and their efficiency during matches and predict the results, in addition to the possibility of watching the ideal performance of certain skills in sports for the player to apply and learn them to the point of mastery.

Abu Arida (2021) also believes that the use of various artificial intelligence applications in the education and training process is commensurate with different swimming skills, considers the individual differences between learners, responds to their interests, and contributes to the development of their physical abilities to reach the highest levels.

Swimming is among the areas that have been directly affected in keeping pace with modern scientific and technological development with artificial intelligence applications in the practical and theoretical aspect, whether in the processes of teaching skills for different types of swimming or through training and development mechanisms to improve the time and performance of swimmers. As swimming is a complete sport that is not equivalent to a sport for the growth of the ideal physical composition of swimmers, it is also a humanitarian sport that enables the individual to save himself and preserve his life and keep the danger away from him and others, and it is a way to save people who are about to drown (Abu Eid, 2008).

The importance of practicing sports activity in general and swimming in particular increases among people with disabilities, as Goodman (2002) pointed out that the importance of practicing sports activity for people with disabilities is doubled, as it is not only preventive, but it also amounts to rehabilitation due to their lack of movement resulting from their disability directly or indirectly. Abu Eid (2004) also pointed out that the practice of swimming activity works to develop the skill level in swimming among individuals with motor disabilities.

The importance

1- It is one of the few studies in the Jordanian environment (within the limits of the researcher's knowledge) Which examines the possibility of using artificial intelligence applications in teaching basic skills in swimming to people with motor disabilities.
2- This study contributes to identifying the importance of using artificial intelligence applications in education and training, especially with people with disabilities.
3- The researcher believes that this study will save effort, energy, and time in teaching basic skills in swimming among people with motor disabilities.

The problem

There are many challenges facing workers in the field of training and teaching swimming to people with disabilities at the present time, so it was necessary to consider the efficiency of the trainers and work to be up to the desired goals. To reach this stage, we must search for factors that contribute to the good productivity and efficiency of trainers in some circumstances through which to influence the educational process in order to interact with training programs and their artificial applications with high efficiency and guide students towards achieving goals. Swimming is one of the water sports that contribute to the growth of the ideal physical composition of its practitioners, and mastering its various skills enables the individual to save himself and maintain his life and ensure his safety and the safety of others, and through the researcher's experience in teaching and training swimming and given that some classrooms may be interspersed with certain circumstances that hinder the entry of participants to the swimming pool, such as the blessed month of Ramadan or during emergency circumstances, as happened during the Corona pandemic (2019) Which constituted a major obstacle at the beginning to the continuity of education, and since technology began a while ago to invade various health, industrial, agricultural, educational and other vital fields, the problem of the study appeared to the researcher, through which he believes in the need to use artificial intelligence techniques in teaching and training swimming among people with motor disabilities, where Haider (1991) mentioned That hearing some sound effects such as guidance, applause, speech and guidance all lead to accelerate learning and economy with the effort expended, by answering the following study questions.

Questions

1- Is there a statistically significant effect at the level of significance (α ≤ .05) between the pre- and post-measurements of the use of the proposed program to learn backstroke skills among people with motor disabilities using artificial intelligence applications for the experimental group?
2- Is there a statistically significant effect at the level of significance (α ≤ .05) between the pre- and post-measurements of using the traditional method on learning backstroke skills among people with motor disabilities of the control group.
3- Is there a statistically significant effect at the level of significance (α ≤ .05) on learning backstroke skills in the two-dimensional measurements between the experimental and control groups.

Objectives

1- Identify the impact of the proposed educational program using artificial intelligence applications on learning basic skills in backstroke among people with motor disabilities.
2- The significance of the differences between the experimental and control groups in the level of learning backstroke skills among people with motor disabilities.

METHODOLOGY

The researcher used the experimental method to suit the nature of the study using the experimental design of two groups, one experimental and the other control.

Participants

The study participant consisted of students with motor disabilities at Hashemite University who were registered for the first semester of the academic year 2023/2024, amounting to (45) students.

Sample

The members of the study sample, numbering (22) students, were deliberately selected from the total community to study according to the conditions (disability in one of the upper or lower limbs, and to adhere until the end of the educational program, and not to be fluent in swimming skills) to equalize the two groups, especially in tribal measurements. They were divided into two groups randomly, so that the experimental group consisted of (12) students, and the control group consisted of (10) students. Table 1 shows the equivalence of the two groups in growth variables.

Table 1. Arithmetic averages, standard deviations, range, and torsion among the sample members in the experimental and control groups.

Growth variables/ unit of measure	**Control Group (10)**				**Experimental Group (12)**			
	Average	Deviation	Range	Torsion	Average	Deviation	Range	Torsion
Length/Meter	172.9	6.48	20	0.19	173	6.68	20	0.42
Weight/kg	76.6	4.11	23	1.19	76.2	3.93	15	1.11
Age/Year	19.2	1.54	4	-0.41	19.4	1.34	4	0.77

By reviewing Table 1, we note that the sample is homogeneous in terms of torsion, where the torsion values of the length variable for the control and experimental sample were (0.19 and 0.42), for the weight variable, the value was (1.19 and 1.11), and for the age variable, the torsion for the two samples was (-0.41 and 0.77), and these values all range between (± 3), which indicates that the two samples are homogeneous.

Tools

After reviewing the specialized references and previous studies such as the study (Al-Shorman et al, 2023), the study of Abu Eid (2008), the study of (Abu Eid et al, 2023) and the study of (Abu Eid, 2021), where the researcher benefited from it in building and designing the proposed educational program for basic skills in backstroke, and he designed the program in proportion to the members of the study sample in terms of the nature of the exercises and skills that suit the nature of motor disability based on the use of artificial intelligence applications in education.

Procedures for the authenticity of tests

Arbitrators were consulted from professors in Jordanian universities and specialists in the field of physical education and special education, numbering (4) arbitrators, to ensure the sincerity and appropriateness of these tests through apparent honesty, to express their opinions and observations about the tests, and after retrieving the tests from the arbitrators, the data on the arbitrators' responses was unloaded, as the percentage of arbitrators' approval of the tests reached 80%, where they made some suggestions and amendments to the method of performing or measuring some tests. The tests under study were nominated for their suitability for the members of the study sample, and the researcher took these suggestions into consideration.

Procedures for the stability of tests

To ensure the stability of the tests, the researcher applied the selected tests to a sample of five students other than the study sample on 8/10/2023 in the Hashemite University swimming pool, and the results were unloaded into special tables in order to conduct the necessary statistical treatment to ensure the stability of the tests, as the tests were repeated on the selected sample a week after the first tests. Then the researcher calculated the Pearson correlation coefficient to find the degree of stability of the tests through the method of testing and re-testing and the degree of stability was as in Table 2.

Table 2. Correlation coefficient (Pearson) and Cronbach alpha for study tests.

Test	Pearson correlation coefficient	Cronbach alpha coefficient
Leg stroke tests	0.78	0.80
Tests for arm movements	0.77	0.82
Total Backstroke Compatibility Tests	0.89	0.91

Table 2 indicates that all correlation coefficients are statistically significant at the significance level ($\alpha \leq .05$) and that the Cronbach alpha coefficient as an indicator of internal consistency of the test indicates a high degree of stability of the tests used in the study.

The proposed educational program using artificial intelligence applications was also presented to a group of arbitrators in the field of swimming and special education, numbering (5) to express their opinions and observations and to ensure the sincerity of the program and its suitability to the objectives of the study and the nature of the sample members through virtual honesty, and after retrieving the program from the arbitrators, the data on the arbitrators' responses was unloaded, as the percentage of arbitrators' approval of the program reached 87%. Where they presented some proposals and amendments to the method of performing some skills commensurate with the nature of motor disability, The researcher took these suggestions into account, and the program under study was nominated for its suitability for the members of the study sample, where the program in its final form consisted of (24) educational units and the time of one unit (45) minutes by three days a week, and the program included teaching some backstroke skills for people with motor disabilities using artificial intelligence applications, whether by presenting them in the form of

PowerPoint slides or displaying YouTube videos and simulation programs for swimming skills. The program was implemented during the period from 15/10 – 7/12/2023.

Statistical analysis

The researcher used statistical treatments that suit the nature of the study, where he used percentages, arithmetic averages, standard deviations, range, torsion, t-test, Pearson's stability coefficient, Cronbach alpha, and analysis of single variance.

RESULTS

The first question, which states "*Are there statistically significant differences at the significance level (α ≤ .05) between the pre- and post-measurement of the experimental group in the skill level in swimming among people with motor disabilities*"?

To verify this question, the researcher calculated the arithmetic mean and standard deviation between the pre- and post-tests of the experimental group, and Table 3 shows the results.

Table 3. Arithmetic averages and standard deviations between the pre- and post-measurements of the experimental group members at the skill level, (n = 12).

Variable	**Unit of measurement**	**Pre-measurement**		**Post-measurement**	
		Arithmetic mean	Standard deviation	Arithmetic mean	Standard deviation
Leg blows	meter	1.80	0.49	9.50	1.35
Arm movements	meter	2.40	0.39	10.10	0.99
Backstroke performance	meter	1.50	0.10	12.80	0.94

It is clear from the presentation of Table 3 that there are apparent differences in the arithmetic averages between the pre- and post-measurements among the members of the experimental group in the skill level. To determine the sources of these differences, a single variance analysis was used, and Table 4 illustrates the results.

Table 4. The source of variance, the sum of squares, the mean of squares, the value of "*F*" and the level of significance between the pre- and post-measurements of the experimental group members. (n = 12).

Variable	**Unit of measurement**	**Source of variance**	**Sum of squares**	**Degree of freedom**	**Mean of squares**	**Value of "*F*"**	**Level of significance**
Leg blows	meter	Between groups	85.73	1	98.73	79.13	.00*
		Inside groups	17.84	10	1.44		
		Total	114.45	11			
Arm movements	meter	Between groups	98.92	1	87.92	77.52	.00*
		Inside groups	45.33	10	1.33		
		Total	657.45	11			
Backstroke performance	meter	Between groups	125.12	1	111.00	89.65	.00*
		Inside groups	9.10	10	0.33		
		Total	145.10	11			

*Note. * There is a positive effect at the significance level (α ≤ .05).*

It is clear from the previous table that the *p*-value ranged between (77.52 and 89.65) and these values are considered a function at the level of significance (α ≤ .05).

The second question, which states that "*Are there statistically significant differences at the significance level (α ≤ .05) between the pre- and post-measurement of the control group in the skill level in backstroke among people with motor disabilities*"?

To verify this question, the researcher calculated the arithmetic mean and standard deviation between the pre- and post-tests of the control group, and Table 5 shows the results.

Table 5. Arithmetic averages and standard deviations between the pre- and post-measurements of the members of the control group in the skill level. (n = 10).

Variable	**Unit of measurement**	**Pre-measurement**		**Post-measurement**	
		Arithmetic mean	Standard deviation	Arithmetic mean	Standard deviation
Leg blows	meter	1.75	0.33	8.25	1.35
Arm movements	meter	2.33	0.37	6.25	0.99
Backstroke performance	meter	1.40	0.10	8.20	0.94

It is clear from the presentation of Table 5 that there are apparent differences in the arithmetic averages between the pre- and post-measurements among the members of the control group in the skill level. To determine the sources of these differences, a single variance analysis was used, and Table 6 illustrates the results.

Table 6. The source of variance, the sum of squares, the mean of squares, the value of "*F*" and the level of significance between the pre- and post-measurements of the control group members. (n = 10).

Variable	**Unit of measurement**	**Source of variance**	**Sum of squares**	**Degree of freedom**	**Mean of squares**	**Value of "*F*"**	**Level of significance**
Leg blows	meter	Between groups	85.73	1	98.73	79.13	.00*
		Inside groups	17.84	8	1.44		
		Total	114.45	9			
Arm movements	meter	Between groups	98.92	1	87.92	77.52	.00*
		Inside groups	45.33	8	1.33		
		Total	657.45	9			
Backstroke performance	meter	Between groups	125.12	1	111.00	89.65	.00*
		Inside groups	9.10	8	0.33		
		Total	145.10	9			

*Note. * There is a positive effect at the significance level (α ≤ .05).*

It is clear from the previous table that the *p*-value ranged between (77.52 and 89.65) and these values are considered a function at the level of significance (α ≤ .05).

The third question, which reads: "*Are there statistically significant differences at the level of significance (α ≤ .05) in the dimensional measurements of the experimental and control groups in the level of backstroke skills using artificial intelligence applications*"?

To verify this question, the researcher calculated the arithmetic mean and standard deviation between the two-dimensional tests of the experimental and control groups, and Table 7 shows the results.

It is clear from the presentation of Table 7 that there are apparent differences in the arithmetic averages between the two-dimensional measurements in the experimental and control groups. To determine the sources of these differences, a single variance analysis was used, and Table 8 shows the results.

Table 7. Arithmetic averages and standard deviations of the two-dimensional measurements for the members of the experimental and control groups.

Variable	Unit of measurement	Control group		Experimental group	
		Arithmetic mean	Standard deviation	Arithmetic mean	Standard deviation
Leg blows	Meter	8.25	1.35	9.50	1.35
Arm movements	Meter	6.25	0.99	10.10	0.99
Backstroke performance	Meter	8.20	0.94	12.80	0.94

Table 8. The source of variance, the sum of squares, the average of squares, the value of "*F*" and the level of significance between the two-dimensional measurements of the members of the experimental and control groups.

Variable	Unit of measurement	Source of variance	Sum of squares	Degree of freedom	Mean of squares	Value of "*F*"	Level of significance
Leg blows	Meter	Between groups	8.12	1	8.12	20.26	.00*
		Inside groups	7.28	8	0.40		
		Total	15.36	9			
Arm movements	Meter	Between groups	14.21	1	14.21	8.90	.00*
		Inside groups	28.88	8	1.60		
		Total	43.16	9			
Backstroke performance	Meter	Between groups	125.00	1	125.0	4.77	.00*
		Inside groups	470.00	8	26.11		
		Total	595.00	9			

*Note. * There is a positive effect at the significance level ($\alpha \leq .05$).*

It is clear from the previous table that there are statistically significant differences in all variables (arm movements, leg strokes, backstroke performance).

DISCUSSION

Table 3 indicates that there are statistical differences and a clear development in the skill level of some backstroke skills among people with motor disabilities (members of the experimental group) who underwent a proposed educational program using some artificial intelligence applications. Table 4 also indicates that all values were a function at the level of significance (α ≤ .05), which indicates the positive impact of the proposed program on the speed of learning the selected swimming skills, and the researcher believes that the use of artificial intelligence applications in teaching swimming skills to people with motor disabilities was very useful in the process of motor memory and mental perception of the skill before and during the application of the skill, which enhanced the ideal performance of the skill when the members of the study sample in the experimental group by following up on intelligence applications artificial and at different times when the study sample, Saeed et al. (2020) also stated that the use of technology in education facilitates the learning process of motor skills by analysing the skill and presenting it in an easy and attractive way, which helps to speed up its learning and comprehension. This is what Abu Arida (2021) pointed out, and I agree with the study of (Wei et al, 2021).

Table 5 also indicates that there are statistical differences in the skill level of some of the backstroke skills of the members of the control group who have undergone a traditional educational program to teach backstroke skills to people with motor disabilities, and Table 6 indicates that all values were a function at the level of significance (α ≤ .05), which indicates the skill improvement among the members of the control group and the researcher attributes this to the natural result of performing the exercise, skill and gaining practical experience in addition to the skill of sensation and habituation. On the water in the pool Which leads to a clear improvement in the skill level. Saeed et al. (2020) stated that the teaching methods used for swimming, whether through verbal explanation or the performance of a model in front of students, give a clear idea of how to properly perform the various swimming skills, and through exercise, repetition and correction of mistakes, learning is done well and mastering the required skills. Where El-Khouly (2001) pointed out that the practice of physical activity may reflect on the life of the individual and develop his vital organs and give activity and vitality to his health and contribute to the process of motor learning. This delegation agreed with the study of Abu Eid (2004), which indicated a positive and noticeable improvement in the skill level of the members of the study sample.

Table 7 also indicates that there are statistical differences in the skill level in the post-tests of some backstroke skills among members of the experimental and control groups and in favour of the experimental group who used artificial intelligence applications to learn swimming skills among people with motor disabilities during the proposed program.

Table 8 also indicates that all values were a function at the level of significance ($\alpha \leq .05$), which indicates the positive impact of the proposed program on the speed of learning the selected swimming skills, and the researcher believes that the use of artificial intelligence applications in teaching swimming skills was very useful in the process of motor memory and mental perception of the skill among people with motor disabilities members of the experimental group, and this is what Abu Arida (2021) pointed out. As the use of artificial intelligence applications in teaching motivates students, improves the learning process and increases the efficiency of the teaching process by deviating from the routine pattern adopted in teaching, which may sometimes boring students, which enhanced the ideal performance of the skill among the members of the study sample in the experimental group by following up on artificial intelligence applications at different times when the study sample, Where Essam and Ayyad mentioned (2021) Many artificial intelligence applications that are used in the sports field simulate the reality of sports, where audio-visual videos related to artificial intelligence help the trainee by storing and analysing the data that is recorded during the performance of the skill to know the performance of the players and their efficiency and predict the results in addition to the possibility of watching the ideal performance of certain skills in swimming for the player to apply and learn them to the point of mastery, Hussain (2000) and (Kozub, 2002) that the use of auditory aids with the learner and activate his ability to think contributes to the formation of a better form of movement so that the skill is analysed accurately, in addition to that the word and music during training accelerate the learning process and banish boredom and the result of the current study agreed with the study of Abu Arida (2021), and (Wei et al, 2021)

CONCLUSIONS

- The proposed program to teach basic skills in backstroke among people with motor disabilities has a positive effect on the development of the skill level in swimming among (people with motor disabilities) members of the study sample of the experimental group.
- The proposed program for teaching basic skills in swimming has a positive impact on the development of the skill level in swimming among people (with motor disabilities) members of the study sample of the control group.
- The proposed program for teaching basic skills in swimming using artificial intelligence applications has a positive impact on the development of the skill level in swimming among the members of the experimental and control groups and for the benefit of the experimental group.

Recommendations

- Applying the proposed educational swimming program for basic skills in backstroke for people with motor disabilities using artificial intelligence applications, as it greatly affected the speed of learning basic skills in backstroke among the sample members.
- Providing Jordanian libraries with references and specialized sources using artificial intelligence applications in training and education.
- Diversity in the use of teaching methods for motor skills for people with motor disabilities.
- Graduating trained and specialized cadres to deal with people with motor disabilities in modern educational ways using artificial intelligence applications.

AUTHOR CONTRIBUTIONS

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SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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REVIEW ARTICLE

Monitoring internal and external load management in female basketball: A narrative review

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ABSTRACT

Monitoring load management in female basketball is essential for optimizing performance and minimizing injury risks. This narrative review consolidates current practices and advancements in monitoring both internal and external loads among female basketball players. A comprehensive literature search was conducted across PubMed, Scopus, and Web of Science databases to identify research focusing on load management in female basketball. Methods utilized for monitoring internal loads include heart rate tracking, rate of perceived exertion (RPE), and biochemical markers, while external loads are assessed through GPS tracking, accelerometers, local positioning systems (LPS), and ultra-wideband (UWB) technology. Recent technological advancements, particularly the use of LPS and UWB systems, have significantly enhanced the precision and reliability of load monitoring, providing real-time, accurate data on player movement and performance. These systems complement traditional methods, offering valuable insights into the physical demands and well-being of athletes. Integrating both internal and external load monitoring is vital for developing tailored training programs that optimize player performance and reduce injury risks. Future research should focus on standardizing protocols and exploring novel technologies to further enhance load management strategies in elite women's basketball.

Keywords: Workload, Female basketball, Performance analysis, Match analysis, Training analysis.

Cite this article as:
Muñoz-Andradas, G., Navarro, R. M., Djuricic, N., & Serrano, C. (2025). Monitoring internal and external load management in female basketball: A narrative review. *Journal of Human Sport and Exercise, 20*(2), 742-752. https://doi.org/10.55860/ja4mnz34

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Submitted for publication February 04, 2025.
Accepted for publication March 14, 2025.
Published March 26, 2025.
Journal of Human Sport and Exercise. ISSN 1988-5202.

doi: https://doi.org/10.55860/ja4mnz34

INTRODUCTION

Basketball is a collective sport that involves high-intensity, intermittent actions, requiring players to combine technical, tactical, and physical abilities to succeed (Matthew & Delextrat, 2009). The sport is characterized by frequent changes in speed and direction, jumps, sprints, and physical contact, making it highly demanding both physically and mentally (Narazaki et al, 2009). In sports science, workload refers to the total physical and physiological demands placed on athletes during training and competition. Gabbett (2016) defines workload as the cumulative amount of stress that is applied to an athlete's body, which, when properly managed, can enhance performance and reduce injury risks. Monitoring workload is essential to prevent overtraining, allowing for the optimization of training programs and recovery strategies (Gabbett, 2016).

Internal load (IL) refers to the physiological and psychological stress experienced by athletes during training and competition. Understanding the external load demands of basketball games is fundamental for effective training planning and programming Reina et al. (2019). Despite some prior research, there is a notable scarcity of information on external load (EL) during official games in high-level women's basketball. This scarcity is evident in professional female basketball as well, where limited studies have focused on quantifying external load during competitive matches. Given this gap, it is essential to examine the existing studies that address this issue.

For instance, Reina et al. (2019) examined training and competition load in elite female basketball players, highlighting the need for more detailed and specific studies in this area. Similarly, Matthew & Delextrat (2009) investigated the physiological demands on elite female basketball players, finding that they experience significant cardiovascular and metabolic stress during competition. These studies underscore the importance of understanding both internal and external loads to optimize performance and reduce injury risks.

Svilar et al. (2018) have further emphasized the need for more precise methodologies to track and analyse both types of loads in basketball. Similarly, Puente et al. (2017) highlighted that tailored approaches to load monitoring are crucial for optimizing performance and minimizing injury risks. Despite these efforts, a pressing need remains for more comprehensive and current research to develop evidence-based training and recovery strategies specifically suited to elite women's basketball players (Impellizzeri et al., 2019).

Furthermore, recent efforts have been made to investigate external load differences between elite basketball teams involved in separate competitions. For instance, a study by Ujaković et al. (2024) explored differences in load demands, highlighting the increasing focus on this topic. External load, which includes factors such as movement patterns, distances covered, accelerations, and decelerations, has been analysed in depth by Conte et al. (2015) and Reina et al. (2019), offering key insights into the physical requirements of players. In parallel, internal load, which is driven by physiological markers like heart rate and blood lactate concentration, has been thoroughly examined by Matthew and Delextrat (2009) and Rodríguez-Alonso et al. (2003), demonstrating the significant physiological demands faced by athletes during competition. Those findings underline the importance of understanding both external and internal loads to optimize training and improve performance in female basketball players.

METHODOLOGY AND RESULTS

The search for articles related to the monitoring of both external load and internal load in female basketball was conducted using a comprehensive approach across multiple scientific databases, including Web of Science (WOS), PubMed, and MEDLINE.

Table 1. Data extracted from the articles reviewed.

Authors	Year	Quartile	Subject	Gender	Competition	Quantification	Technology used	Results
Arenas-Pareja et al.	2023	Q2	Menstrual Cycle Influence on Load in Basketball	Female	Challenge women's league	14 training sessions, IL and EL	WIMUPROTM (Real Track Systems, Almería, Spain) with Ultra-wideband (UWB) and Clue mobile app	Different phases of the menstrual cycle affect both internal and external load, impacting recovery and performance.
Conte et al.	2015	Q1	Time-motion analysis in basketball	Female	Serie A1 women's Italian first division basketball	5 home games (3 Serie A1 games and 2 Euroleague games), EL	Camera (Sony HD AVCHD HDR CX115, Tokyo, Japan) and Time motion analysis	Short, frequent sprints interspersed with lower intensity periods.
Delextrat et al.	2015	Q3	Match activity analysis	Female	Spanish National Division 1 League (Liga Femenina 1)	3 matches for each team, EL	Lince Multiplatform sport analysis software	Highlights distinct movement patterns by playing position.
Lorenzo Gasperi et al.	2023	Q4	Performance influenced by menstrual cycle phase	Female	Lithuanian Women's Basketball League (LMKL)	External load (Player Load per minute), Internal load (RPE), Pre-game recovery (TQR), Menstrual phase	Microsensors (Catapult S5), Excel spreadsheet for RPE and TQR, Menstrual phase calculated by calendar method	Better shooting and rebounding performances during the follicular phase. Higher RPE and better pre-game recovery linked to better performance
Narazaki et al.	2009	Q1	Physiological demands of basketball	Female	National Collegiate Athletic Association (NCAA) Division II	IL and EL	The VO2 was measured by the system with a sampling frequency of 0.05 Hz, while HR was monitored using a Polar watch (Polar Electro Oy, Kempele, Finland) and RPE was assessed using Borg's original (i.e., 6–20) scale (Borg, 1982)	High physiological demands, intermittent high-intensity activity.
Peterson & Quiggle	2016	Q3	Wearable device validation	Female	Division I National Collegiate Athletics Association basketball	Data collection began 3 weeks prior to competition and concluded amidst the final week of regular season competition. EL	Catapult Optimeye (Catapult Sports, Melbourne, Australia),Tensiomyiography and accelerometer device	Effective for monitoring performance during competition.
Reina et al.	2017	Q4	Training and competition load	Female	Extremadura state level competition (Spain)	2 games, a friendly match and a competition game, IL and EL	Heart rate band Garmin®, Wimu® device	Intense competition loads not replicated in training.
Scanlan et al.	2012	Q2	Physiological demands in competition	Female	Queensland Basketball League	8 competitive matches, IL	Accusport Lactate Analyser (Boehringer, Mannheim, Germany), Polar Team System (Polar Electro, Oy, Kempele, Finland)	High physical demands, particularly in short bursts of activity.
Svilar et al.	2018	Q2	Load monitoring system in basketball	Female	Spanish	IL and EL, two basketball leagues, ACB (Liga Endesa, 1st Spanish Division) and the Euroleague, in the 2016/2017 season.	S5 devices (Catapult Innovations, Melbourne, Australia) and RPE	Significant load differences observed across competitions.
Vencúrik et al.	2017	Q3	External and internal load analysis	Female	Slovenian	IL and EL	Canon HG10 (Canon Inc., Tokyo, Japan), telemetric system Suunto Team (Suunto Oy, Vantaa, Finland)	Variations in load during different match intensities.

Each database was thoroughly explored to identify relevant studies that addressed the quantification and analysis of these loads in elite and professional female basketball players. The articles retrieved from these searches were systematically organized in Table 1, where detailed information about each study is provided. The key insights and findings from these studies are critically analysed and discussed in the subsequent sections, highlighting their contributions to the understanding of load management in female basketball.

Understanding internal load: Concepts and measurements

Key methods for monitoring internal load in female basketball players include heart rate monitoring, rate of perceived exertion (RPE), and biochemical markers (Impellizzeri, Marcora, & Coutts, 2019). Heart rate monitoring is a widely used method that provides insights into cardiovascular strain (Vencúrik, Šťastný, & Leskošek, 2017; Matthew & Delextrat, 2009). Studies, such as those by Vencúrik et al. (2017), highlight its importance in understanding the internal load during various exercise intensities. RPE is another effective tool that involves athletes rating their perceived exertion on a scale, typically from 6 to 20, providing a subjective measure of internal load. Biochemical markers, including cortisol and creatine kinase, offer objective measures of physiological stress and muscle damage, respectively (Mexis et al., 2023). Research by Matthew & Delextrat (2009) demonstrated the utility of these markers in assessing stress and recovery in elite athletes. These methods collectively help in tailoring training programs to individual needs, optimizing performance, and minimizing the risk of overtraining and injuries. Understanding and effectively measuring internal load are critical for developing comprehensive load management strategies in female basketball (Gabbett, 2016; Kellmann, 2010).

Further, Narazaki et al. (2009) studied the physiological demands of competitive basketball by measuring oxygen consumption, heart rate, and blood lactate concentration during practice games. The findings indicated that aerobic metabolism plays a significant role in basketball, suggesting the importance of aerobic conditioning for players. Similarly, Scanlan et al. (2012) highlighted the demands placed on female basketball players during competitive games, emphasizing the necessity of monitoring internal load to optimize training and performance.

The physiological demands of competitive female basketball are characterized by a high reliance on both aerobic and anaerobic energy systems, as demonstrated by the work of Narazaki et al. (2009). Their research found that players maintain an average VO2 of 33.4 mL/kg/min, representing 66.7% of their VO2max during games. This high aerobic demand underscores the importance of endurance conditioning to support the intermittent high-intensity efforts required throughout a basketball match. Despite spending 56.8% of game time walking, players engage in frequent bursts of high-intensity activity, covering 4500–5000 meters per game.

Further supporting these findings, research into heart rate and blood lactate levels has provided a more detailed picture of the internal load sustained by players. Vencúrik et al. (2017) found that female players operate at approximately 88.4% of their HRmax throughout games, suggesting that maintaining high-intensity conditioning is crucial across all positions. Similarly, the work of Rodriguez-Alonso et al. (2003) showed elevated blood lactate levels in female players during competition, further highlighting the significant anaerobic demands of the sport.

Given the intensity of female basketball, monitoring internal load through physiological markers such as heart rate and blood lactate is critical. As demonstrated by Vencúrik et al. (2017), consistent heart rate data across player positions indicates that basketball places a uniform demand on players. This suggests that load management strategies should focus on conditioning all players to handle prolonged high-intensity efforts.

Additionally, lactate monitoring, as discussed by Rodriguez-Alonso et al. (2003), helps to capture the anaerobic stress placed on athletes, making it a valuable tool for tailoring recovery and training intensities.

Assessing external load: Techniques and tools

External load refers to the physical demands placed on athletes, which can be quantified using various tools and techniques. In female basketball, GPS tracking, accelerometers, and other wearable technologies are commonly employed (Conte et al., 2015; Reina et al., 2019; Scanlan et al., 2020). GPS tracking systems are valuable for measuring movement patterns, distances covered, and speeds during games and training sessions (Reina, García-Rubio, & Ibáñez, 2017; Boyd et al., 2013). Technology has revolutionized the way external loads are monitored in female basketball. Devices such as GPS tracking systems, accelerometers, and other wearable technologies are commonly used to measure movement patterns, distances covered, and speeds during training and games (Peterson & Quiggle, 2016). These devices provide detailed and real-time data on players' physical load, allowing for accurate assessment of their performance and well-being (Montgomery et al., 2010; Conte et al., 2015; Svilar et al., 2018). The incorporation of these technologies in female basketball has significantly improved the precision and ease of load monitoring, offered a better understanding of physical demands and helped to optimize training programs (Vázquez-Guerrero et al., 2019; Vickery et al., 2014).

Vickery et al. (2014) demonstrated the effectiveness of GPS in providing detailed activity profiles in elite women's field hockey, a method that can be effectively applied to basketball as well. Accelerometers, which measure acceleration forces, are another essential tool for quantifying the intensity and volume of physical activity (McGinnis et al., 2013). These devices are extensively used in sports science to monitor and analyse the physical demands placed on athletes during both training and competition. Boyd et al. (2013) further validated the use of 5 Hz GPS units, demonstrating their reliability in team sports. Moreover, wearable technologies, such as heart rate monitors and fitness trackers, offer real-time data on various physiological parameters, thereby enhancing the precision of external load monitoring (Scanlan et al., 2020; Staunton et al., 2021; Svilar et al., 2018). Time-motion analysis, as highlighted by Conte et al. (2015), is also crucial in understanding the physical demands of basketball. This is further supported by Narazaki et al. (2009), who provided insights into the physiological demands during competitive basketball, laying the foundation for assessing external load in female basketball. Together, these technologies and analytical methods form a robust framework for assessing external load, enabling coaches and sports scientists to optimize training regimens, improve performance, and reduce injury risk.

Additional studies have provided further insights into the external load demands in female basketball. For example, Reina et al. (2017) examined whether training loads reflect the demands of actual competition in women's basketball. Their findings indicated significant differences between training and competition, particularly in heart rate and steps per minute, suggesting that training programs should be adjusted to better match the intensity of competition. Conte et al. (2015) conducted a time-motion analysis of elite Italian women's basketball games, revealing that players engage in high-intensity activities (HIA) for approximately 8.5% of the total game time. The analysis found that the distances covered during sprints were predominantly short, ranging between 1 and 5 meters. This pattern of short, frequent sprints, interspersed with periods of lower-intensity movement, underscores the importance of developing repeated sprint ability (RSA), a critical component of performance in elite women's basketball. These insights inform training practices by emphasizing the need to focus on RSA to meet the physical demands of the sport. Peterson and Quiggle (2016) discussed the effectiveness of using wearable technology to monitor physical activity and recovery, emphasizing the importance of data accuracy and consistency. Conte et al. (2015) conducted a time-motion analysis of elite Italian women's basketball games, revealing that players engage in high-intensity activities

(HIA) for approximately 8.5% of the total game time. The analysis found that the distances covered during sprints were predominantly short, ranging between 1 and 5 meters. This pattern of short, frequent sprints, interspersed with periods of lower-intensity movement, underscores the importance of developing repeated sprint ability (RSA), a critical component of performance in elite women's basketball. These insights inform training practices by emphasizing the need to focus on RSA to meet the physical demands of the sport.

However, the study by Reina, Mancha, and Ibáñez (2017) revealed that the external load demands in training sessions do not reach the same levels as during games. Players experience higher intensity in competition, both in terms of heart rate and distance covered per minute. This discrepancy between training and competition underscores the need to adjust training sessions to better reflect the actual physical demands of games. By doing so, performance can be improved and, more importantly, the risk of injury can be minimized.

Narazaki et al. (2009) complement these findings, emphasizing the intermittent nature of basketball, which requires both high-intensity activity and periods of active recovery. Players are constantly switching between different types of movement, such as running, walking, and sprinting, which increases the total physical load. This suggests that training should not only focus on intensity but also on the players' ability to quickly adapt to changes in activity.

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In line with these studies, Scanlan et al. (2012) observed that players perform a large number of short sprints and changes of direction during games, which creates a significant physical load. This is fundamental to preparing players for the rigors of the game and ensuring that they can maintain a high level of performance throughout the season.

Advancements in female player monitoring

Technological advancements have significantly enhanced the monitoring of internal and external loads in female basketball players. Wearable technology, such as smartwatches and fitness trackers, has become increasingly popular, providing real-time data on various physiological parameters (Conte et al., 2015; Svilar et al., 2018). The integration of wearable devices in female basketball has revolutionized performance monitoring by offering continuous data on heart rate, activity levels, and sleep patterns (Puente et al., 2017). Advanced software and analytics platforms have emerged, enabling sophisticated analysis of large datasets specific to female basketball players. Wearable technology has been applied extensively in team sports, including female basketball, where advanced analytics play a crucial role in interpreting complex data to inform training decisions (Conte et al., 2015). For example, studies have used biometric sensors to measure sweat composition and muscle oxygenation, providing deeper insights into the physiological state of female basketball players. Accurate monitoring tools are essential for understanding the differences between internal and external load during competition in female basketball, as highlighted by research on load management specific to this sport (Cavedon et al., 2015). These technological advancements facilitate a more comprehensive understanding of load management, helping to tailor training programs, monitor recovery, and ultimately enhance performance while reducing injury risks in female basketball players.

The studies examining the menstrual cycle's influence on internal and external loads in professional female basketball players reveal a nuanced relationship between performance, physiological stress, and injury risk. Gasperi et al. (2023) found that menstrual cycle phases, particularly the follicular phase, correlate with improved game performance metrics such as shooting efficiency and rebounds. The study by Arenas-Pareja et al. (2023) investigates the effects of the menstrual cycle on internal and external load variables in professional female basketball players. The research highlights how different phases of the menstrual cycle, particularly during menstruation and ovulation, significantly impact both physical exertion and recovery processes. Using detailed monitoring of heart rate, accelerations, and decelerations, the study provides evidence of the physiological fluctuations female athletes experience throughout their menstrual cycle. Moreover, Vico-Moreno et al. (2022) identified a significant association between irregular menstrual cycles and an increased risk of ankle and knee injuries, highlighting the importance of monitoring both physiological and biomechanical stress during the cycle. These findings align with Narazaki et al. (2009), who emphasized the overall physiological demands of basketball, underscoring the need for individualized training strategies that account for menstrual phases to optimize performance and reduce injury risks.

Advances in technology have enhanced the monitoring of internal and external loads in female basketball players. Gasperi et al. (2023) demonstrated that tracking systems combined with subjective measures, such as perceived exertion, allow for a detailed understanding of how performance metrics fluctuate across the menstrual cycle. This approach provides valuable insights into tailoring training and recovery strategies to individual athletes, ensuring optimal performance and reducing injury risks. Wearable technologies, including accelerometers and heart rate monitors, have further supported real-time load management, highlighting the importance of individualized monitoring in elite female basketball.

DISCUSSION

Integrating internal and external load monitoring in female basketball presents both challenges and benefits. A holistic approach to load management ensures a comprehensive understanding of an athlete's physiological and physical demands. Scanlan et al. (2012) highlighted the physiological and activity demands during competition, providing crucial data for tailored training programs. Reina et al. (2017) emphasized the importance of monitoring both training and competition loads to optimize performance and reduce injury risks, showing significant differences between internal and external load measures. Narazaki et al. (2009) revealed that female players experience unique physical stresses that must be addressed in training regimens, while Conte et al. (2015) identified distinct movement patterns and intensities in elite women's basketball games. Recent advances, like those from Gasperi et al. (2023), demonstrated that menstrual cycle phases affect performance metrics such as shooting efficiency and rebounds, while Arenas-Pareja et al. (2023) found peaks in external load values during ovulation. Peterson and Quiggle (2016) explored the relationship between accelerometer loads and TMG readings in female collegiate basketball, showing that TMG could effectively detect neuromuscular fatigue based on external load changes. Svilar et al. (2018) further emphasized that a combination of sRPE and accelerometery offers strong correlations, particularly with decelerations and changes of direction, reinforcing the need for combined internal and external monitoring.

Delextrat et al. (2015) focused on match activity by position, revealing that point guards performed more sprints and guards covered more ground compared to centres. Finally, Reina et al. (2017) demonstrated higher heart rate values and more steps per minute in real competition compared to training, highlighting the need for training loads to reflect competitive demands. In addition, Vencúrik et al. (2017) analysed heart rate responses in semi-elite female basketball players during competitive games, finding no statistically significant differences between positions or game halves, indicating that the physiological demands remain high regardless of player roles or game phases. This reinforces the importance of implementing training programs that account for consistent physiological demands across various positions.

CONCLUSIONS

Internal and external load relationship

Research on elite female basketball players reveals a strong link between internal and external load. High-intensity actions like sprints and changes of direction dominate game dynamics, leading to significant internal physiological responses such as elevated heart rate and lactate levels. Monitoring both types of loads is crucial for optimizing performance and reducing injury risks.

Physiological responses to game intensity

External load metrics correlate with internal physiological strain, highlighting the importance of tracking both to manage player fatigue and recovery effectively. This dual-monitoring approach ensures athletes maintain peak performance throughout games and training.

Practical application

Advanced monitoring technologies

GPS and wearable sensors provide real-time data on movement and intensity, enabling dynamic training adjustments. This technology improves performance optimization and injury prevention, offering tailored training strategies based on precise, individualized data.

Gender-specific training protocols

Recognizing the physiological differences between male and female athletes, gender-specific training programs are essential. Tailoring load management to female athletes reduces the risk of overtraining and fatigue while optimizing performance.

Comprehensive load management

Combining internal and external load monitoring allows for personalized recovery strategies and balanced training intensities, preventing overtraining. This approach helps sustain player performance across the competitive season.

Uniform intensity across positions

All player positions experience high-intensity demands in elite basketball. Training programs must enhance both aerobic capacity and anaerobic power to meet these demands, ensuring readiness for the physical challenges of competition.

Repeated Sprint Ability (RSA) training

Conte et al. identified that players frequently engage in sprints covering distances between 1-5 meters. This highlights the necessity of focusing training on developing repeated sprint ability (RSA) to match the high-intensity demands during games.

Injury risk management

Studies by Gabbett and Drew & Finch emphasize the importance of balancing training loads. By maintaining this balance, coaches can minimize the risk of injury while ensuring that players perform at their peak during competitions.

The frequency with which these movements are performed during competition highlights the need for training sessions to include specific exercises that mimic these demands, such as repeated sprints and quick changes of direction.

AUTHOR CONTRIBUTIONS

Muñoz-Andradas G., conceptualization; Serrano C., Navarro R. M., Nenad D. and Muñoz-Andradas G., methodology; Muñoz-Andradas G., writing-original draft; Serrano C. and Navarro R. M., writing-review and editing; Nenad D. and Muñoz-Andradas G., visualization; Serrano C. and Navarro R. M., supervision.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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