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.

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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.

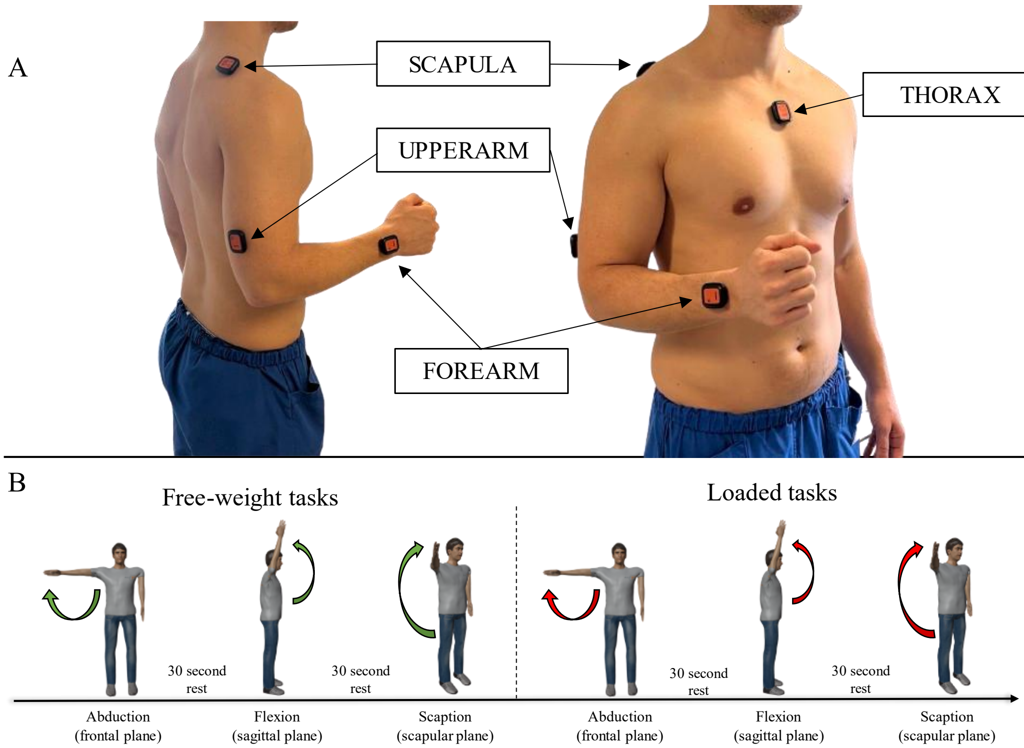

Figure 1. A. Xsens DOT sensor placement. One sensor placed at the level of the sternum (referred to as thorax), one sensor placed superior to the midpoint of the scapular spine (referred to as scapula), one sensor placed on the posterior aspect of the distal humerus (referred to as upper arm), and one 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 Dominant vs Non-Dominant			Controls Dominant vs Non-Dominant			Tennis Player vs Controls Dominant			Tennis Player vs Controls 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.

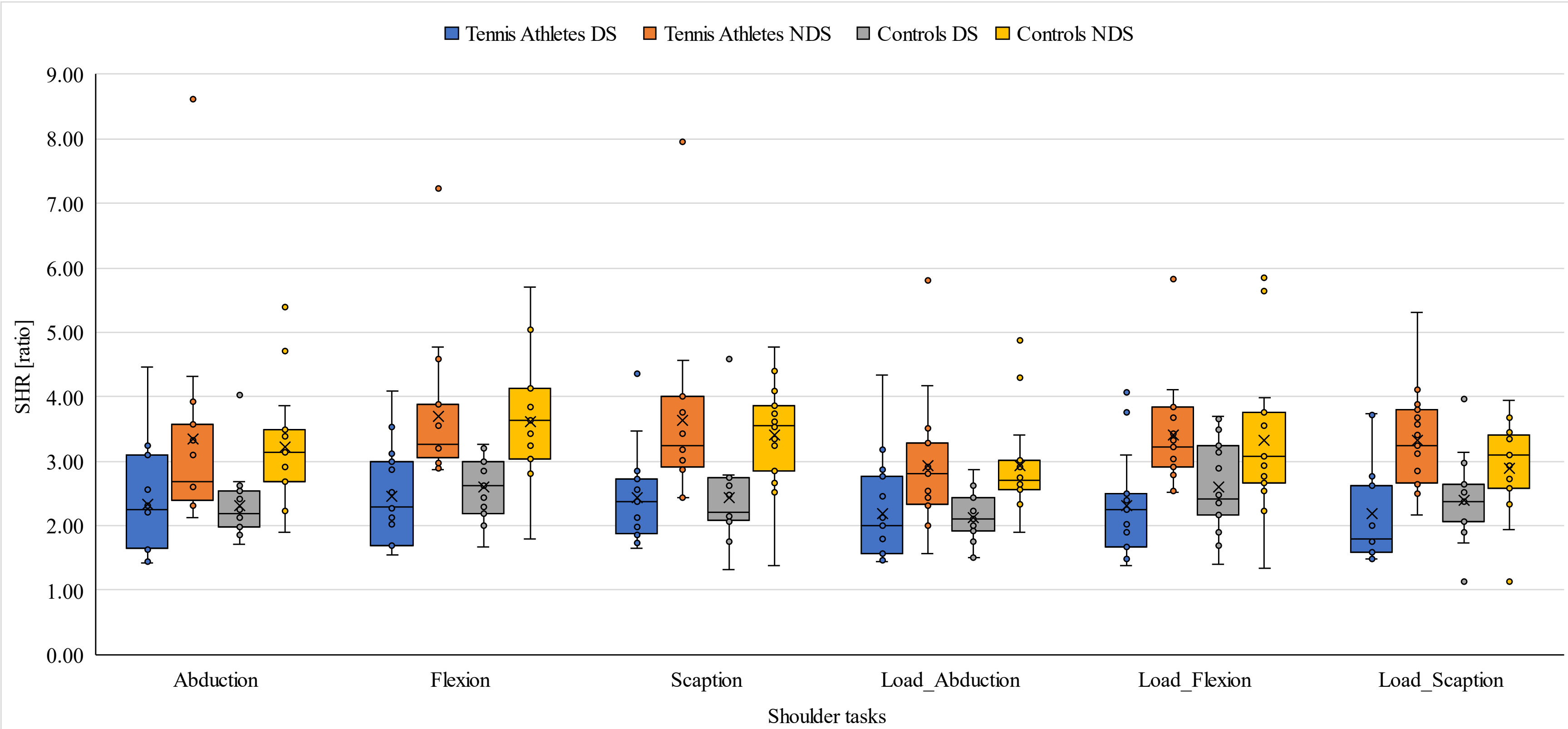

Figure 2. Scapulohumeral rhythm (SHR) during unloaded and loaded shoulder abduction (frontal plane), flexion (sagittal plane) and scaption (scapular plane).

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.

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