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.

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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.

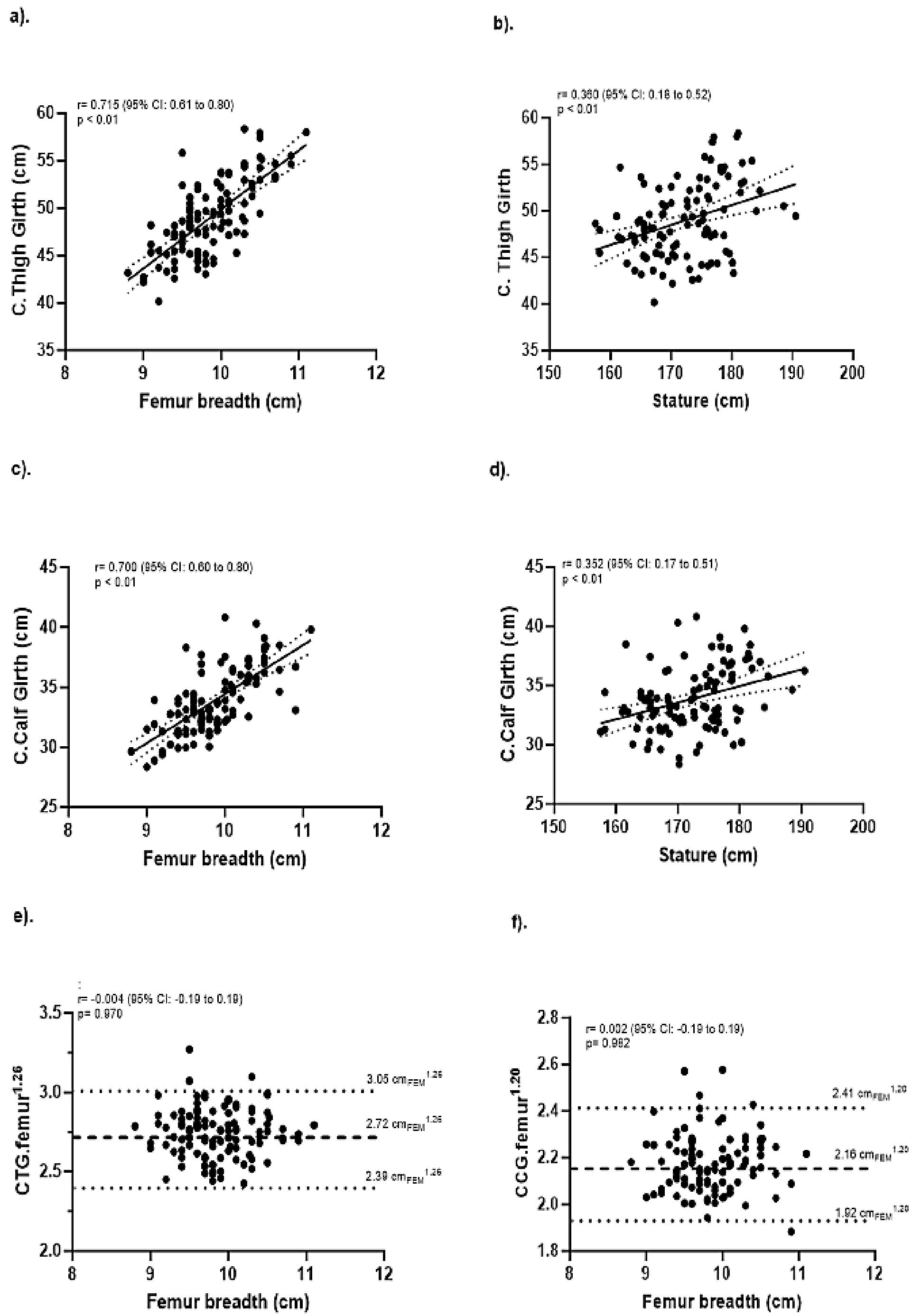
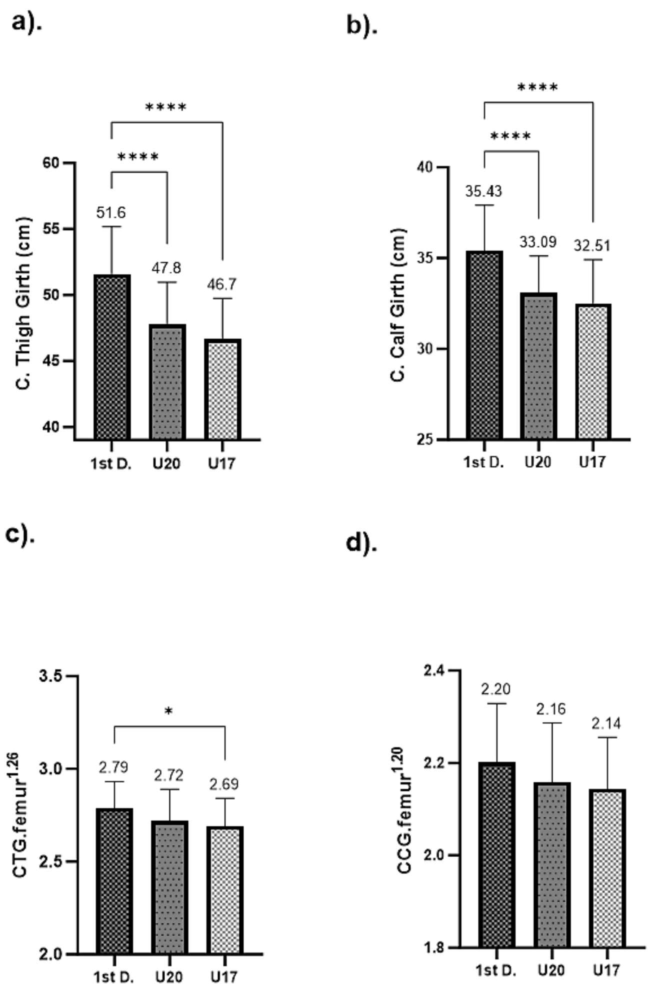


Figure 1. Relationship of Corrected Thigh Girth to Femur breadth (**a**), and to Stature (**b**); relationship of Corrected Calf Girth to Femur breadth (**c**), and to Stature (**d**); and correlations between power functions and respective size descriptors for Corrected Thigh Girth (**e**) and for Corrected 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.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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