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Maturity status effects on torque and muscle architecture of young soccer players

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ABSTRACT

This study investigated the effects of maturity status on knee extensor torque and vastus lateralis architecture of young soccer players. Thirty-four males aged 13–18 years were divided into two groups: pubescent (PUB, $n = 15$) and postpubescent (POSP, $n = 19$). Torque by angle interaction was established for absolute [$F(2.649, 84.771) = 9.066, p < 0.05$] and relative to body mass [$F(2.704, 86.533) = 4.050, p < 0.05$] isometric torque with the POSP group showing greater values. Muscle volume torque-angle relationship was similar between groups. Absolute, relative to body mass, and relative to muscle volume concentric and eccentric torque-velocity relationship showed a non-significant interaction but a significant group effect in favour the POSP group for absolute and concentric torque relative to body mass. Torque-angle and torque-velocity relationship normalized by body mass allometric exponents showed a non-significant interactions and group effects. Muscle thickness (3.6 ± 0.6 vs. 3.8 ± 0.6 cm), fascicle length (8.3 ± 1.4 vs. 8.9 ± 1.6 cm) and pennation angle (15.0 ± 2.3 vs. 14.3 ± 3.2 degrees) was similar between PUB and POSP groups, respectively. Maturity status did not show a significant effect on muscle architecture and on isometric and dynamic torques when allometrically normalized.

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KEYWORDS

Muscle volume; cross-sectional area; pennation angle; fascicle length; allometry

Introduction

Muscle force typically increases progressively from 8 to 18 years of age (De Ste Croix, Deighan, & Armstrong, 2003; Nedeljkovic, Mirkov, Kukulj, Ugarkovic, & Jaric, 2007; Van Praagh & Dore, 2002). During this period, there is a growth spurt in response to biological maturation, resulting in height, muscle and bone mass increases, and muscle architectural changes, which lead to significant increases in absolute muscle force and torque (Debernard, Robert, Charleux, & Bensamoun, 2011; De Ste Croix, Armstrong, Welsman, & Sharpe, 2002; De Ste Croix et al., 2003; Kubo, Kanehisa, Kawakami, & Fukunaga, 2001; Morse et al., 2008; Nedeljkovic et al., 2007; O'Brien, Reeves, Baltzopoulos, Jones, & Maganaris, 2010a; Tonson, Ratel, Le Fur, Cozzone, & Bendahan, 2008). Muscle force is an important variable in sports performance, and its increase is often accompanied by an improvement in soccer-specific abilities like kicks, jumps, sprints, defence, and changes in motion direction and joint stability (Hoff & Helgerud, 2004). The optimal period (window of opportunity) to improve physical, technical, and physiological capacities has been postulated to occur between the ages of 12 and 16 years, during the course of maturation (Balyi & Hamilton, 2004).

Proper identification and quantification of the biological maturation effects on muscle force and muscle architecture has been a long-standing problem (Bouchant, Martin, Maffiuletti, & Ratel, 2011; Herzog et al., 2011) in the

selection process and talent identification of young athletes (Cunha et al., 2011; De Ste Croix et al., 2003; Ford et al., 2011; Malina, Eisenmann, Cumming, Ribeiro, & Aroso, 2004; Nedeljkovic et al., 2007; Ostojic et al., 2014; Philippaerts et al., 2006; Vaeyens et al., 2006; Van Praagh & Dore, 2002). From a soccer players' talent identification and/or talent development perspective, the interpretation of physical fitness characteristics may be more problematic due to maturity-related differences. Previous findings indicate that independent of chronological age and body size, biological maturation exerts a positive effect on explosive power, strength, speed, aerobic performance, and sport-specific skills (Coelho et al., 2010; Cunha et al., 2011; De Ste Croix et al., 2003; Ford et al., 2011; Malina et al., 2004; Nedeljkovic et al., 2007; Van Praagh & Dore, 2002). Consequently, biological maturation may have a strong impact on the talent identification and/or talent development process. It is well known that soccer systematically excludes late maturing boys and favours early maturing boys (Figueiredo, Goncalves, Coelho, & Malina, 2009; Malina et al., 2004; Ostojic et al., 2014). In contrast, recent studies have shown evidence that physical fitness is not affected by biological maturation in soccer players (Cunha et al., 2011, 2016; Figueiredo, Coelho, & Malina, 2011; Wrigley, Drust, Stratton, Atkinson, & Gregson, 2014).

Caution should be taken when interpreting studies that examine the effects of biological maturation on sports

performance, as maturation is often based on chronologic age. In addition, muscle forces are often measured for isometric contractions or few dynamic contractions, while muscle architecture, a morphological parameter that is directly related to biological maturation and maximal force production, is typically ignored (Debernard et al., 2011; De Ste Croix et al., 2003; Kubo et al., 2001; Morse et al., 2008; O'Brien, Reeves, Baltzopoulos, Jones, & Maganaris, 2009; O'Brien et al., 2010a; O'Brien, Reeves, Baltzopoulos, Jones, & Maganaris, 2010b). There is a need to understand the effects of biological maturation on muscle architecture, muscle force, the force-length and the force-velocity relations (Barrett & Harrison, 2002; Borges, Vaz, De La Rocha Freitas, & Rassier, 2003; Marginson & Eston, 2001). In addition, methodological procedures, neuromuscular factors, intrinsic muscle factors, and normalization methods may affect the interpretation of muscle force and muscle torque (Barrett & Harrison, 2002; De Ste Croix et al., 2002, 2003; Jaric, 2002; Nedeljkovic et al., 2007; Tonson et al., 2008).

Although the relation between muscle strength and body size has been frequently studied, the normalization of the measured strength relative to body size has been performed inconsistently (Jaric, 2002, 2003). Dividing muscle force by body mass (kg) is known as the standard normalization ($\text{Force} \cdot \text{kg}^{-1}$), and has been historically used to control for the body size effect. However, this method has been criticized based on the fact that body mass and muscle force/torque are not linearly related, as muscle force increases at a lower rate and muscle torque at a greater rate than body mass (De Ste Croix et al., 2003; Jaric, 2002; Nevill, Holder, Baxter-Jones, Round, & Jones, 1998). Therefore, normalization methods that are specific for muscle force and muscle torque are necessary. Allometry has been recommended to adjust the effects of body size over muscle force or torque (Jaric, 2002; Nevill et al., 1998). Allometry is based on the equation ($Y = aX^b$), where (a) is a constant, and (b) is the scaling exponent corresponding to the body size descriptor. Y is the dependent variable (e.g., force or torque), while X is the body size descriptor (e.g., body mass, muscle volume, cross-sectional area). Proper choice of the allometric exponent (b) allows for appropriate comparisons between subjects of different body size and body composition (Jaric, 2002). Establishing proper normalization procedures allows for distinguishing which factors account for the increases in muscle force/torque in growing adolescent athletes.

The purpose of this study was to determine whether maturity status exerts effects on appropriately normalized isometric and dynamic muscle torques and on muscle architecture of young soccer players.

Methods

Subjects

The sample comprised 34 First Division amateur male players from the Brazilian Soccer League. All participants were engaged in formal training (5 to 8 training sessions per week, 60–120 minutes per session) and completed one game per week during an 8-month competitive season. All players

had at least 2 years of experience as soccer players. The study was approved by the University Research Ethics Board (Project ID#: 2008082), and was conducted in compliance with the standards set by the Declaration of Helsinki. Participants and their legal guardians were informed of the experimental protocol and the potential risks, and provided written informed consent prior to participation.

Procedures

Participants were divided into two groups according to their maturity status, including 15 players in the pubescent group (PUB), and 19 in the postpubescent group (POSP). Biological maturation was assessed by a trained healthcare professional using the criteria described by Tanner (Tanner, 1962), based on the genitalia (size and shape of the penis and scrotum) and on pubic hair development. Pubertal status was defined as Tanner stages 2, 3, and 4, and post-pubertal as Tanner stage 5. Height and body mass were determined using a stadiometer and a scale (Urano PS 180A, 0.01-m and 0.1 kg resolution; Rio Grande do Sul, Brazil), respectively. Rectus femoris and vastus intermedius muscle thickness (MT), knee-extensor muscle volume (MV), rectus femoris cross-sectional area (CSA), and vastus lateralis pennation angle (PA) and fascicle length (FL) were measured using ultrasonography, and strength was determined using isokinetic dynamometry.

Muscle architecture

An ultrasound device with a 6-cm linear array transducer and a sampling frequency of 7.5 MHz (SSD 4000, 51 Hz, ALOKA Inc., Tokyo-Japan) was used to determine architectural variables (MV, MT, CSA, FL and PA) of the knee extensor muscle group. Image J software (version 1.44x, NIH, USA) was used for all muscle architectural variables analyses.

Muscle volume

The knee extensor muscle group (vastus lateralis, vastus medialis, vastus intermedius and rectus femoris) muscle volume was determined according to the method reported by Miyatani, Kanehisa, Ito, Kawakami, and Fukunaga (2004). The following equation was used to estimate the knee extensors (Y_{KE}) muscle volume:

$$Y_{KE} = (X_1 \times 320.6) + (X_2 \times 110.9) - 4437.9$$

Where: Y = Muscle volume (ml); X_1 = Muscle thickness of rectus femoris and vastus intermedius (cm); and X_2 = Limb length (cm).

For ultrasound measurements, the midpoint on the anterior surface of the thigh (i.e., between the femur's greater trochanter and the joint cavity that includes the femur and the tibial condyles) were carefully identified and marked. Next, the transducer was covered in gel and placed perpendicular to the muscle and bone. Ultrasound measurements were obtained without pressing the probe onto the skin surface. The subcutaneous fat and muscle interface, as well as the

muscle and bone interface, were identified. These interfaces served as references for measuring MT, defined as the distance between the superficial (rectus femoris) and the deep (vastus intermedius) muscle aponeuroses. Muscle volume was measured using the vastus intermedius and the rectus femoris MT. The intraclass correlation coefficient for the test-retest of MT measurements was $r = 0.972$ (Miyatani et al., 2004). The coefficient of repeatability at each measurement site ranged from 1.3 mm to 1.8 mm. These values were 1.7% to 5.5% of the corresponding thickness mean value (Miyatani et al., 2004).

Cross-sectional area

The ultrasound images used for the determination of the knee extensors' MV were also used to measure the rectus femoris CSA. Rectus femoris CSA was calculated by a planimetric technique (Image J software version 1.44x, NIH, USA) after the inner echogenic line of the rectus femoris was outlined by a movable cursor on a frozen image (Seymour et al., 2009).

Fascicle length and pennation angle

FL and PA were obtained at rest from the vastus lateralis muscle using ultrasound imaging. The ultrasound probe was positioned longitudinally in the approximate direction of the muscle fibres, at 50% of the thigh length, with the hip and knee joints fully extended (Maganaris, Baltzopoulos, Ball, & Sargeant, 2001). When FL exceeded the probe length, FL was estimated using the methodology proposed by Blazeovich, Gill, and Zhou (2006). FL was defined as the fascicular distance between the deep and superficial aponeuroses. PA was defined as the angle formed between the muscle fascicle and the deep aponeurosis (Maganaris et al., 2001). FL and PA were determined as the mean of three fascicles obtained on each ultrasound image. FL (in cm) was normalized by the thigh length (FL_n) to allow for between-subjects comparison.

Isokinetic dynamometry

An isokinetic dynamometer (Biodex Medical System, Shirley – NY, USA) was used to determine the torque-angle and torque-velocity relations. After a 5-minute warm up on a cycle ergometer, athletes were sat on the dynamometer chair, with the lateral femoral epicondyle aligned with the dynamometer's axis of rotation. The hip and knee joints were kept at an angle of 90° ($0^\circ =$ full extension). The trunk and thigh were stabilized with belts, and the knee maximal joint range of motion was determined. Familiarization trials were performed by executing one maximal voluntary contraction at knee angles of 30° , 60° , and 90° , and three concentric-eccentric contractions at angular velocities of $60^\circ \cdot s^{-1}$, $120^\circ \cdot s^{-1}$ and $240^\circ \cdot s^{-1}$.

For the torque-angle relation, subjects performed one maximal voluntary contraction at six different joint angles (30° , 45° , 60° , 75° , 90° and 105° ; $0^\circ =$ full knee extension) to assess isometric peak torque. Isometric peak torque was defined as the highest torque achieved during isometric contractions for each joint angle. A 1.5 min interval was observed between consecutive contractions to avoid fatigue.

For the torque-velocity relation, athletes performed three maximal concentric-eccentric knee extensor contractions at six different angular velocities ($30^\circ \cdot s^{-1}$, $60^\circ \cdot s^{-1}$, $90^\circ \cdot s^{-1}$, $120^\circ \cdot s^{-1}$, $180^\circ \cdot s^{-1}$ and $240^\circ \cdot s^{-1}$) to access concentric and eccentric peak torque. A 2.0 min interval was observed between consecutive velocities to avoid fatigue. Peak concentric and eccentric torques were defined as the highest torques achieved among the three dynamic contractions in concentric and eccentric actions, respectively. All athletes received verbal encouragement to reach maximal effort during the maximal effort tests, as well as visual feedback of their performance.

Torque signals were collected using a Windaq software (sampling frequency = 2000 Hz per channel) and stored on a personal computer for further analysis in MATLAB (MATLAB version 7.3.0.267, MathWorks, Inc., Natick, MA, USA).

Statistical analysis

Normality of the data distribution was evaluated using the Shapiro-Wilk test, and homoscedasticity of the variables was assessed using Levene's test. The mean and standard deviation values were used for descriptive purposes. Physical and muscle architecture between-groups comparisons were performed using independent t-tests. Effect size (ES) Cohen's d was calculated for these comparisons (Hopkins, 2000; Hopkins, Marshall, Batterham, & Hanin, 2009) and interpreted as follows (Hopkins et al., 2009): < 0.20 (trivial), 0.20 to 0.59 (small), 0.60 to 1.19 (moderate), 1.20 to 1.99 (large), 2.0 to 3.9 (very large), > 4.0 (nearly perfect).

Pearson's analysis of correlation was used to investigate correlations among muscle architecture, torque, and body size descriptors. The magnitude of correlations was interpreted as follows: trivial ($r < 0.1$), small ($0.1 < r < 0.3$), moderate ($0.3 < r < 0.5$), large ($0.5 < r < 0.7$), very large ($0.7 < r < 0.9$), and nearly perfect ($r > 0.9$) (Hopkins et al., 2009).

Allometric exponents were calculated using natural logarithms (\ln) of absolute torque (Nm) and \ln of body descriptors, such as body mass (Kg) and MV (ml). The allometric exponents were calculated using the initial allometric model: $Y = a \times X^b \times \epsilon$. Values of (a) and (b) were obtained from linear regressions of the logarithmic regression transformations in the form of: $\ln Y = \ln a + b \ln X + \ln \epsilon$. Where: (a) is a scale constant and (b) is the scaling exponent corresponding to a body size descriptor. Y corresponds to the value of the dependent variables (\ln isometric torque, \ln concentric torque, and \ln eccentric torque) and X corresponds to the body size descriptors (\ln body mass and \ln MV). The homogeneity of the allometric exponents was verified using ANCOVA with the inclusion of an interaction term (group \times \ln body size descriptors). The statistical assumptions used to estimate the exponents were investigated using methods previously described in the literature (Cunha et al., 2011; Jaric, 2002; Nevill, Ramsbottom, & Williams, 1992; Valente-Dos-Santos et al., 2015, 2013; Zoeller et al., 2008). For an allometric model to be deemed appropriate, there should be no significant correlation between the allometrically scaled torque ($Nm \cdot kg^{-b}$ or $Nm \cdot ml^{-b}$) and the body descriptor (body mass or muscle volume). Correlation coefficients that do not approach zero,

regardless of whether they are statistically significant, would suggest that the proportional allometric model was not completely successful in rendering isokinetic torque outputs independent of body size (Carvalho et al., 2012; Nevill et al., 1992). In addition, the homogeneity of regression slopes between PUB and POSP groups could indicate that the allometric model was successful in scaling torque independent of maturational group and body size descriptor (Cunha et al., 2011, 2016; Zoeller et al., 2008).

Two-way ANOVAs for repeated measures were used to analyse within-group and between-group main effects (isometric, concentric, and eccentric torque) as well as group-angle and group-velocity interactions. Bonferroni post-hoc testing was used to establish the location of significant differences between groups. The assumption of sphericity was confirmed by the Mauchly test. Where sphericity was violated, a Greenhouse-Geiser adjustment was implemented. The within-group comparisons are not shown. Partial eta-squared (η^2) was calculated as a measure of ES. Values of 0.01, 0.06 and above 0.15 were considered as small, medium and large, respectively (Cohen, 1988).

Statistical analyses were conducted using SPSS (version 19.0, SPSS, Inc., IBM Company; NY, USA) and GraphPad Prism (version 5.03, GraphPad Software, La Jolla, CA) softwares. The level of significance was set at $p < 0.05$.

Results

As expected, the POSP group athletes were older, and had greater body mass, height, thigh length and MV compared to the PUB group athletes (Table 1). There were no between-group differences for the remaining muscle architectural variables (FL, FL_n, PA) and training time.

The correlations among isometric, concentric, and eccentric torque with body size descriptors were as follows: body mass ($0.589 < r < 0.838$; $p < 0.05$), MV ($0.362 < r < 0.610$; $p < 0.05$). Following normalization of the isometric and dynamic torques by body mass (Nm.kg^{-1}) and MV (Nm.ml^{-1}), they remained significantly correlated with body mass ($0.410 < r < 0.450$; $p < 0.05$), and MV ($-0.424 < r < -0.593$, $p < 0.05$). The allometric exponents calculated for body mass and MV are described in Table 2. MV did not provide a significant allometric exponent to dynamic torque ($p > 0.05$), and the assumption of homogeneity among the exponents was broken. Body mass provided significant allometric exponents to isometric and dynamic torques (Cunha et al., 2011; Jaric, 2002; Nevill et al., 1992; Zoeller et al., 2008).

The absolute torque-angle (Nm) relationship showed a significant torque by angle interaction [$F(2.649, 84.771) = 9.066$, $p < 0.05$, ES = 0.221], and angle and group main effects ($p < 0.05$) with the POSP group showing greater absolute isometric torque values compared to the PUB group (Figure 1(a)). The torque-angle relative to body mass (Nm.kg^{-1}) relationship showed a significant torque by angle interaction [$F(2.704, 86.533) = 4.050$, $p < 0.05$, ES = 0.112], and angle and group main effects ($p < 0.05$) with the POSP group showing greater isometric torque relative to body mass values compared to the PUB group (Figure 1(b)). The muscle volume torque-angle (Nm.ml^{-1})

Table 1. Participant's characteristics according to their maturity status.

Variable	PUB	POSP	ES	ES _q
Age (years)	14.5 ± 0.8	16.6 ± 1.2*	2.059	Very large
Body mass (kg)	64.2 ± 7.8	76.6 ± 7.0*	1.673	Large
Height (m)	1.73 ± 5.3	1.82 ± 6.3*	0.015	Trivial
Training time (years)	4.6 ± 2.3	4.2 ± 2.3	0.173	Trivial
Limb length (cm)	43.4 ± 1.5	45.4 ± 2.0*	1.131	Moderate
Muscle thickness (cm)	3.6 ± 0.6	3.8 ± 0.6	0.333	Small
Muscle volume (ml)	1526 ± 307	1814 ± 410*	0.793	Moderate
CSA (cm ²)	9.8 ± 1.9	10.3 ± 2.0	0.256	Small
FL (cm)	8.3 ± 1.4	8.9 ± 1.6	0.332	Small
FL _n (cm)	0.19 ± 0.03	0.20 ± 0.03	0.333	Small
PA (degrees)	15.0 ± 2.3	14.3 ± 3.2	0.251	Small

Data expressed as the mean and standard deviation (mean ± SD), where * = significantly different from pubescent group; FL = vastus lateralis fascicle length; FL_n = vastus lateralis normalized fascicle length; PA = vastus lateralis pennation angle; CSA = rectus femoris cross-section area; PUB = pubescent group; POSP = postpubescent group; ES = Cohen's d effect size; ES_q = qualitative effect size. Significance ($p < 0.05$).

relationship showed a non-significant torque by angle interaction [$F(2.682, 80.455) = 2.812$, $p > 0.05$, ES = 0.086] and group effect ($p > 0.05$), resulting in similar values of isometric torque relative to muscle volume between groups, but a significant angle effect was observed ($p < 0.05$) (Figure 1(c)).

The absolute eccentric torque-velocity (Nm) relationship showed non-significant torque by velocity interaction [$F(5, 160) = 1.567$, $p > 0.05$, ES = 0.047], but showed significant velocity and group main effects ($p < 0.05$), with the POSP athletes showing greater absolute eccentric torque values compared to the PUB group (Figure 2(a)). The absolute concentric torque-velocity (Nm) relationship showed a non-significant torque by velocity interaction [$F(3.529, 112.922) = 0.510$, $p > 0.05$, ES = 0.016], but showed significant velocity and group main effects ($p < 0.05$) with the POSP athletes achieving greater values of absolute concentric torque compared to the PUB group (Figure 2(b)). The eccentric torque-velocity relative to body mass (Nm.kg^{-1}) relationship showed a non-significant torque by velocity interaction [$F(3.782, 121.014) = 1.282$, $p > 0.05$, ES = 0.039], and group effect ($p > 0.05$), but a significant velocity effect ($p < 0.05$) (Figure 2(c)). The concentric torque-velocity relative to body mass (Nm.kg^{-1}) relationship showed a non-significant torque by velocity interaction [$F(3.620, 115.853) = 0.499$, $p > 0.05$, ES = 0.015], but significant velocity and group main effects ($p < 0.05$), with the POSP athletes showing greater values compared to the PUB athletes (Figure 2(d)). The muscle volume eccentric torque-velocity (Nm.ml^{-1}) relationship showed non-significant torque by velocity interaction [$F(3.731, 119.378) = 1.240$, $p > 0.05$, ES = 0.037] and group effect ($p > 0.05$), but a significant velocity effect was established ($p < 0.05$) (Figure 2(e)). The muscle volume concentric torque-velocity (Nm.ml^{-1}) relationship showed a non-significant torque by velocity interaction [$F(3.189, 102.060) = 0.412$, $p > 0.05$, ES = 0.013], and group effect ($p > 0.05$), but a significant velocity effect was observed ($p < 0.05$) (Figure 2(f)).

There were no significant differences between the POSP and PUB groups for the torque-angle and torque-velocity relations when torque values were normalized using specific allometric exponents relative to body mass Nm.kg^{-b} (Tables 3–5).

Table 2. Allometric exponents calculated for isometric, concentric, and eccentric knee extensor torques relative to muscle volume (MV) and body mass (BM).

X_i	Y_i	Correlation (X_i, Y_i)			Allometric model [Log $Y_i = \log a + b \cdot \log (X_i) + \log \epsilon_i$]					Correlation ($X_i, Y_i \cdot X_i^{-b}$)		
		Coefficient	(95% CI)	Magnitude	Constant	b-exponent (SE)	R	p value	Ancova (p)	Coefficient	p value	
MV	30° ISO	+0.507	(+0.172 to +0.732)	Large	+2.285	0.37 (0.138)	0.438	0.011*	0.185	+0.117	0.510	
	45° ISO	+0.471	(+0.146 to +0.719)	Moderate	+3.047	0.32 (0.131)	0.409	0.023*	0.855	+0.138	0.437	
	60° ISO	+0.499	(+0.700 to +0.898)	Moderate	+2.311	0.44 (0.156)	0.451	0.007*	0.860	+0.105	0.932	
	75° ISO	+0.521	(+0.177 to +0.743)	Large	+1.919	0.51 (0.160)	0.492	0.003*	0.464	-0.009	0.960	
	90° ISO	+0.442	(+0.259 to +0.730)	Moderate	+2.039	0.48 (0.188)	0.409	0.016*	0.671	+0.002	0.991	
	105° ISO	+0.397	(+0.136 to +0.621)	Moderate	+2.557	0.37 (0.162)	0.378	0.028*	0.375	+0.001	0.999	
	30°·s ⁻¹ CON	+0.393	(+0.004 to +0.657)	Moderate	+3.479	0.25 (0.150)	0.292	0.099	0.777	+0.118	0.506	
	60°·s ⁻¹ CON	+0.362	(+0.120 to +0.617)	Moderate	+3.425	0.26 (0.152)	0.303	0.097	0.749	+0.073	0.682	
	90°·s ⁻¹ CON	+0.381	(+0.132 to +0.898)	Moderate	+2.345	0.40 (0.174)	0.378	0.027*	0.150	-0.018	0.921	
	120°·s ⁻¹ CON	+0.256	(-0.039 to +0.543)	Small	+3.184	0.29 (0.042)	0.279	0.110	0.116	-0.037	0.837	
	180°·s ⁻¹ CON	+0.364	(+0.104 to +0.607)	Moderate	+2.295	0.43 (0.153)	0.447	0.008*	0.377	-0.082	0.645	
	240°·s ⁻¹ CON	+0.454	(+0.238 to +0.671)	Moderate	+1.554	0.29 (0.162)	0.451	0.007*	0.624	+0.009	0.973	
	30°·s ⁻¹ ECC	+0.398	(+0.084 to +0.647)	Moderate	+2.359	0.44 (0.184)	0.388	0.023*	0.222	-0.043	0.810	
	60°·s ⁻¹ ECC	+0.315	(-0.044 to +0.669)	Moderate	+4.190	0.19 (0.120)	0.279	0.129	0.324	0.094	0.595	
	90°·s ⁻¹ ECC	+0.610	(+0.309 to +0.818)	Large	+2.055	0.47 (0.126)	0.558	0.001*	0.221	0.097	0.587	
	120°·s ⁻¹ ECC	+0.402	(+0.080 to +0.731)	Moderate	+2.427	0.42 (0.167)	0.405	0.018*	0.044†	-0.029	0.869	
	180°·s ⁻¹ ECC	+0.473	(+0.167 to +0.727)	Moderate	+2.295	0.43 (0.153)	0.447	0.008*	0.377	0.036	0.839	
	240°·s ⁻¹ ECC	+0.311	(+0.043 to +0.563)	Moderate	+3.130	0.32 (0.156)	0.338	0.051	0.478	-0.027	0.320	
	BM	30° ISO	+0.638	(+0.387 to +0.797)	Large	+0.451	1.08 (0.226)	0.645	<0.001*	0.756	-0.056	0.752
		45° ISO	+0.739	(+0.583 to +0.854)	Very large	-0.185	1.30 (0.214)	0.732	<0.001*	0.061	-0.140	0.824
60° ISO		+0.732	(+0.559 to +0.851)	Very large	+0.280	1.25 (0.200)	0.742	<0.001*	0.486	+0.001	0.995	
75° ISO		+0.775	(+0.591 to +0.903)	Very large	-0.238	1.40 (0.195)	0.786	<0.001*	0.473	-0.024	0.895	
90° ISO		+0.794	(+0.666 to +0.889)	Very large	-0.140	1.57 (0.214)	0.793	<0.001*	0.278	-0.005	0.976	
105° ISO		+0.761	(+0.603 to +0.876)	Very large	-0.087	1.27 (0.196)	0.753	<0.001*	0.352	+0.005	0.975	
30°·s ⁻¹ CON		+0.838	(+0.751 to +0.902)	Very large	-0.096	1.28 (0.160)	0.821	<0.001*	0.619	+0.139	0.435	
60°·s ⁻¹ CON		+0.795	(+0.684 to +0.877)	Very large	+0.244	1.20 (0.174)	0.787	<0.001*	0.527	+0.145	0.415	
90°·s ⁻¹ CON		+0.763	(+0.584 to +0.880)	Very large	-0.532	1.37 (0.421)	0.758	<0.001*	0.539	-0.002	0.990	
120°·s ⁻¹ CON		+0.664	(+0.494 to +0.801)	Large	+0.251	1.19 (0.227)	0.679	<0.001*	0.582	-0.018	0.921	
180°·s ⁻¹ CON		+0.600	(+0.366 to +0.761)	Large	+1.084	1.04 (0.228)	0.627	<0.001*	0.860	+0.001	0.999	
240°·s ⁻¹ CON		+0.727	(+0.539 to +0.865)	Very large	-0.698	1.39 (0.221)	0.742	<0.001*	0.850	-0.003	0.986	
30°·s ⁻¹ ECC		+0.732	(+0.555 to +0.855)	Very large	-0.273	1.38 (0.238)	0.716	<0.001*	0.886	-0.058	0.744	
60°·s ⁻¹ ECC		+0.592	(+0.357 to +0.753)	Large	+1.371	0.99 (0.214)	0.631	<0.001*	0.705	-0.012	0.946	
90°·s ⁻¹ ECC		+0.792	(+0.662 to +0.886)	Very large	+0.607	1.16 (0.175)	0.766	<0.001*	0.311	+0.136	0.444	
120°·s ⁻¹ ECC		+0.665	(+0.500 to +0.807)	Large	+0.368	1.21 (0.226)	0.687	<0.001*	0.889	-0.008	0.962	
180°·s ⁻¹ ECC		+0.598	(+0.374 to +0.785)	Large	+1.084	1.04 (0.228)	0.627	<0.001*	0.860	+0.017	0.925	
240°·s ⁻¹ ECC		+0.589	(+0.364 to +0.748)	Large	+1.332	0.97 (0.225)	0.607	<0.001*	0.890	-0.006	0.974	

Equation used for the calculation of the scaling allometric exponents: $\ln Y = \ln a + b \ln X + \ln \epsilon$, where Y corresponds to dependent variables as isometric (ISO), concentric (CON), and eccentric (ECC) torque (Nm) transformed to natural logarithms, and X corresponds to body size descriptor, such as body mass (kg) and muscle volume (ml). The exponent's homogeneity was verified by ANCOVA, where † means that the homogeneity of the regression slopes has been broken thereby indicating that the allometric model was not successful in scaling torque independent of maturational group and body size ($p < 0.05$); * = b-coefficient statistically significant ($p < 0.05$); b = scaling allometric exponents relative to body size descriptors; 95% CI = 95% confidence interval of b; BM = body mass; MV = muscle volume.

Discussion

To the best of our knowledge, this is the first study in which the effects of maturity status on vastus lateralis muscle architecture, knee extensor torque-angle and torque-velocity relations, normalized by allometry, were verified in young soccer players. Our main findings were that: (1) maturity status did not show a significant effect on isometric, concentric or eccentric torques after allometric normalization; (2) maturity status did not show a significant effect on vastus lateralis muscle architecture (PA, CSA, FL, FLn, MT), except for MV; (3) allometric exponents relative to body mass ($\text{Nm} \cdot \text{kg}^{-b}$) were considered the best way to normalize isometric and dynamic torques in comparison to the standard normalization to body mass ($\text{Nm} \cdot \text{kg}^{-1}$), to the anatomical cross-sectional area ($\text{Nm} \cdot \text{CSA}^{-1}$), and to MV ($\text{Nm} \cdot \text{MV}^{-1}$ and $\text{Nm} \cdot \text{MV}^{-b}$), respectively.

Absolute knee extensor torques (Nm) have been shown to increase progressively by about 300% for boys and young soccer players between 8–21 years of age (De Ste Croix et al., 2003; Nedeljkovic et al., 2007; Van Praagh & Dore, 2002), with an exponential increase during the maturational process (De Ste Croix et al., 2003; Forbes et al., 2009a; Forbes, Sutcliffe,

Lovell, McNaughton, & Siegler, 2009b; Holm, Steen, & Olstad, 2005). A similar behaviour is observed when torque is normalized by body mass, with normalized strength increases varying between 1.5 to 3.1 $\text{Nm} \cdot \text{kg}^{-1}$. Our results about absolute and normalized peak torque are in agreement with previous studies considering chronological age, maturity status, sport, and contraction type (Forbes et al., 2009a, 2009b; Holm et al., 2005).

However, the typical normalization procedures used ($\text{N} \cdot \text{kg}^{-1}$ or $\text{Nm} \cdot \text{kg}^{-1}$) have limitations. The main limitation is that knee extensor force and torque do not scale linearly with body mass, as force increases at a smaller rate and torque at a larger rate than body mass (Jaric, 2002; Nevill et al., 1998). Therefore, normalization to body mass (kg^{-1}) does not capture well the increases in knee extensor force and torque with growth in young soccer players (Bouchant et al., 2011; De Ste Croix et al., 2003; Herzog et al., 2011). Our results show that knee extensor torques remain significantly correlated with body mass after normalization to body mass, because knee extensor torques increase at a greater rate than body mass, with a mean allometric exponent of $b = 1.2$ with a range of $0.97 < b < 1.57$ for isometric and dynamic contractions.

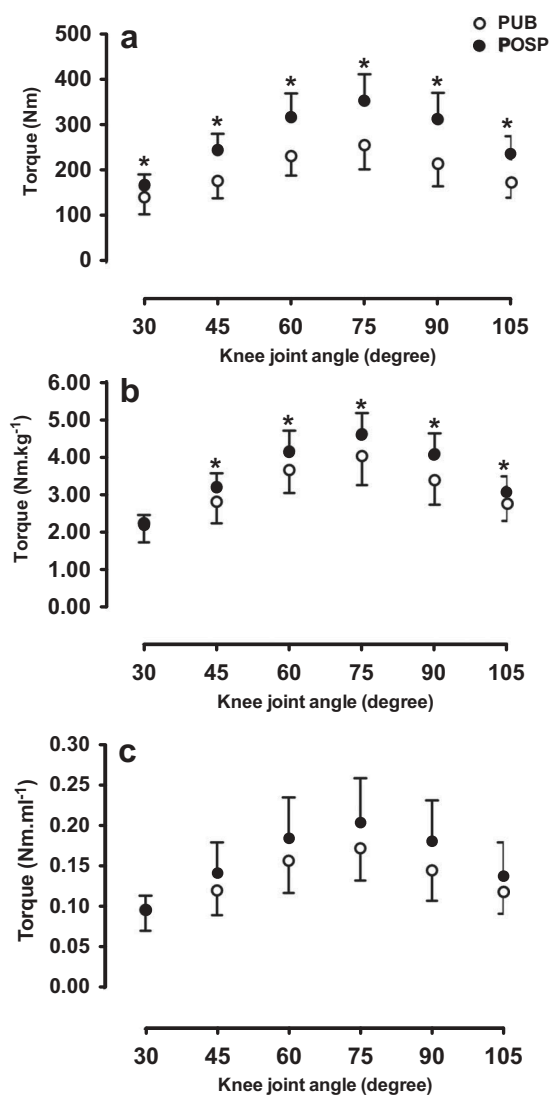


Figure 1. Torque-angle relationship for pubescent (PUB) and postpubescent (POSP) soccer players expressed in (a) absolute; (b) relative to body mass; and (c) relative to muscle volume isometric torque values * Indicates significant difference between groups ($p < 0.05$).

Although it is obvious that children produce less absolute force and torque than adults, it is not obvious how these strength differences change when force and torque are normalized by dimensional variables related to growth and maturation (Bouchant et al., 2011; De Ste Croix et al., 2003; Herzog et al., 2011; Tonson et al., 2008). However, understanding and isolating the effects of training, growth, maturation, and chronological age on muscle force and torque is complex. Several factors may explain the variations in muscle force and torque in children and adolescents. These factors are neuromuscular (voluntary activation of agonist muscles, coactivation

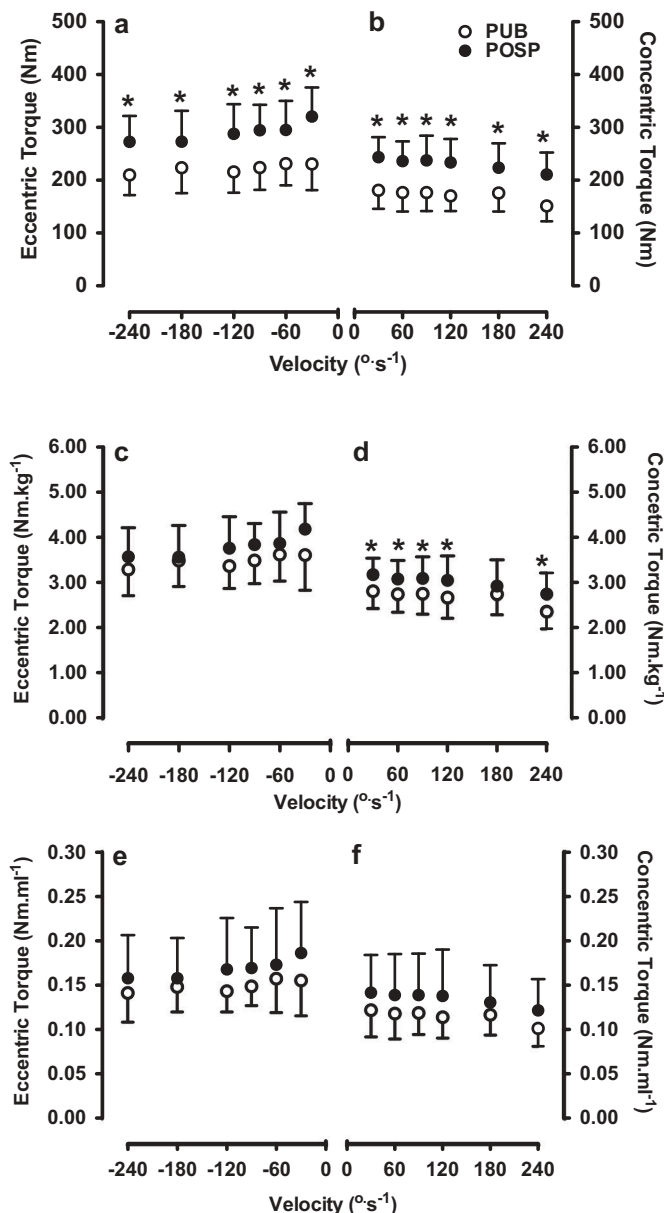


Figure 2. Torque-velocity relationship for pubescent (PUB) and postpubescent (POSP) soccer players expressed in (a) absolute eccentric torque; (b) absolute concentric torque; (c) relative to body mass eccentric torque; (d) relative to body mass concentric torque; (e) relative to muscle volume eccentric torque; and (f) relative to muscle volume concentric torque values. * Indicates significant difference between groups ($p < 0.05$).

of antagonist muscles and muscle coordination), biomechanical (lever arm and joint moment), muscular (tendon stiffness, fibre type, enzymatic activity, muscular glycogen, force-time history of muscle contraction, connective tissue, myofibrillar density and non-contractile material infiltration – e.g. fat infiltration), methodological (contraction type, stability and gravity

Table 3. Isometric torque-angle relationship normalized by allometric exponents relative to body mass of soccer players.

	30° Nm.kg ^{-1.08}	45° Nm.kg ^{-1.30}	60° Nm.kg ^{-1.25}	75° Nm.kg ^{-1.40}	90° Nm.kg ^{-1.57}	105° Nm.kg ^{-1.27}	Interaction Group × Angle	Angle Effect	Group Effect	ES (η^2)
PUB	1.59 ± 0.37	0.81 ± 0.17	1.29 ± 0.23	0.76 ± 0.16	0.32 ± 0.06	0.89 ± 0.16	$p = 0.298$	$p < 0.0001$	$p = 0.2796$	0.037
POSP	1.55 ± 0.18	0.87 ± 0.10	1.40 ± 0.18	0.81 ± 0.09	0.34 ± 0.04	0.96 ± 0.12				

Data expressed as the mean and standard deviation (mean ± SD). PUB = pubescent group; POSP = postpubescent group; ES = partial eta-squared (η^2) effect size; ISO = isometric torque. Significance ($p < 0.05$).

Table 4. Concentric torque-velocity relationship normalized by allometric exponents relative to body mass of soccer players.

	30°·s ⁻¹ Nm.kg ^{-1.28}	60°·s ⁻¹ Nm.kg ^{-1.20}	90°·s ⁻¹ Nm.kg ^{-1.37}	120°·s ⁻¹ Nm.kg ^{-1.19}	180°·s ⁻¹ Nm.kg ^{-1.04}	240°·s ⁻¹ Nm.kg ^{-1.39}	Interaction Group × Velocity	Velocity Effect	Group Effect	ES (η ²)
PUB	0.88 ± 0.12	1.19 ± 0.17	0.59 ± 0.10	1.21 ± 0.22	2.32 ± 0.39	0.47 ± 0.08	<i>p</i> = 0.573	<i>p</i> < 0.0001	<i>p</i> = 0.1350	0.016
POSP	0.94 ± 0.11	1.29 ± 0.17	0.62 ± 0.09	1.33 ± 0.24	2.46 ± 0.49	0.51 ± 0.09				

Data expressed as the mean and standard deviation (mean ± SD). PUB = pubescent group; POSP = postpubescent group; ES = partial eta-squared (η²) effect size; CON = concentric torque. Significance (*p* < 0.05).

Table 5. Eccentric torque-velocity relationship normalized by allometric exponents relative to body mass of soccer players.

	30°·s ⁻¹ Nm.kg ^{-1.38}	60°·s ⁻¹ Nm.kg ^{-0.99}	90°·s ⁻¹ Nm.kg ^{-1.16}	120°·s ⁻¹ Nm.kg ^{-1.21}	180°·s ⁻¹ Nm.kg ^{-1.04}	240°·s ⁻¹ Nm.kg ^{-0.97}	Interaction Group × Velocity	Velocity Effect	Group Effect	ES (η ²)
PUB	0.74 ± 0.18	3.77 ± 0.61	1.79 ± 0.26	1.41 ± 0.21	2.95 ± 0.49	3.73 ± 0.65	<i>p</i> = 0.450	<i>p</i> < 0.0001	<i>p</i> = 0.1974	0.027
POSP	0.80 ± 0.11	4.04 ± 0.72	1.92 ± 0.23	1.51 ± 0.28	3.00 ± 0.59	4.07 ± 0.73				

Data expressed as the mean and standard deviation (mean ± SD). PUB = pubescent group; POSP = postpubescent group; ES = partial eta-squared (η²) effect size; ECC = eccentric torque. Significance (*p* < 0.05).

correction), dimensional (body mass, body mass index, free fat mass, CSA, physiological cross-sectional area – PCSA, FL and MV), structural (PA, FL, MT, CSA, PCSA and MV), and the biological maturation process (Barrett & Harrison, 2002; Bouchant et al., 2011; De Ste Croix et al., 2002, 2003; Herzog et al., 2011; Jaric, 2002; O'Brien et al., 2009, 2010a; Radnor et al., 2018; Tonson et al., 2008; Van Praagh & Dore, 2002).

Biological maturation is a critical variable when analysing strength development in children, adolescents and young athletes, as there is an exponential increase in height, body mass, fat free mass, CSA and MV during maturation (Boisseau & Delamarche, 2000; De Ste Croix et al., 2003; Van Praagh & Dore, 2002), and increases in testosterone, IGF-I production (Boisseau & Delamarche, 2000; De Ste Croix et al., 2003; Van Praagh & Dore, 2002), myelination, nervous system development (Boisseau & Delamarche, 2000; De Ste Croix et al., 2003) and changes in muscle architecture (Debernard et al., 2011; Kubo et al., 2001; Morse et al., 2008; O'Brien et al., 2009, 2010a, 2010b). Our results confirm the obvious changes in body dimensions and MV, but do not support the expected changes in muscle architecture.

Similar to previous studies (De Ste Croix et al., 2002; Fukunaga et al., 2014; Holm et al., 2005; Morse et al., 2008; O'Brien et al., 2009, 2010a; Tonson et al., 2008), maturity status did not show a significant effect on knee extensor torque. Morse et al. (2008) did not find differences between early pubescent children and adults when the gastrocnemius lateralis torque was normalized to CSA. Fukunaga et al. (2014) showed that isometric maximal torques of knee extensor and ankle plantar flexor muscles were not different between pre-pubertal and pubertal groups when normalized to MV. O'Brien et al. (2009) observed significant differences in absolute torques among men, women, and prepubescent boys and girls. However, when torques were normalized by MV, the between-group differences disappeared. Similar results were observed for pre-pubescent children and adults when torques were normalized to PCSA, showing that the torque increase that occurred during biological maturation was not due to the specific tension (force/PCSA) (O'Brien et al., 2010a). This is in agreement with our results.

Studies aimed at determining the effects of biological maturation on knee extensor strength in young soccer players are rare. Holm et al. (2005) conducted an 11-year longitudinal

study aimed at evaluating the development of isokinetic knee extensor torque before, during and after the maturational process. Pubescent subjects showed greater knee extensor and flexor torques than pre-pubescent subjects, but smaller than post-pubescent subjects for absolute torque and for torques normalized by body mass. They concluded that there was a biological maturation effect, with an exponential increase between 12 and 17 years (Holm et al., 2005).

Due to the insufficiency of standard normalization to adequately predict strength of subjects of different chronological ages, different body composition, different maturational status, and different performance levels, allometric scaling has been considered an emergent method that successfully accommodates the nonlinear relationship between body size descriptors and muscle force and torque (Jaric, 2002; Nevill et al., 1998). When the data of the present study were normalized by allometry, no significant differences between maturational groups were observed in the six angles and the 12 different velocities of muscle contraction tested, in contrast to comparisons made with the absolute values (Nm) and the values normalized to body mass (Nm.kg⁻¹).

Our results demonstrate the importance of establishing the best variable for torque normalization. Similar results were shown by De Ste Croix et al. (2002), who concluded that biological maturation did not influence knee flexor and extensor isokinetic torques in boys and girls when height and body mass were controlled by allometry. In the same way, biological maturation has been suggested to have little influence on the strength-size relationship in the lower extremity muscles around puberty (Fukunaga et al., 2014).

Muscle architectural variables have been considered determinants of muscle function. Muscles with a large CSA, MV, and PA are built for great force production, while muscles with long FL are built for high shortening velocity and large excursion (Blazevich, 2006). Muscle architectural variables have been shown to adapt in response to chronic training, detraining, reduced use, immobilization, injury, growth, biological maturation and aging (Blazevich, 2006). Specifically, studies have shown that, through growth and biological maturation, increases occur in PA, FL, MT and CSA (Debernard et al., 2011; Fukunaga et al., 2014; Kubo et al., 2001; Morse et al., 2008; O'Brien et al., 2009, 2010a, 2010b; Tonson et al., 2008). In contrast, our results do not demonstrate a significant effect

of biological maturation on muscle architecture variables, except for MV. Children usually have shorter FL in the vastus lateralis muscle (6.2–7.6 cm) than adolescents (8.0 cm) and adults (6.9–9.4 cm), similar values of PA (15.8–16.2°) as adolescents (16.6°) and adults (13.2–21.0°), but smaller values than athletes (18–23°) (Kanehisa, Muraoka, Kawakami, & Fukunaga, 2003; Kearns, Isokawa, & Abe, 2001; Kubo et al., 2001; O'Brien et al., 2010a, 2010b). FL, FL_n and PA in our study were similar for pubescent and postpubescent soccer athletes. One explanation for these results might be that increases in FL typically occur during the pre-pubescent period, whereas substantial increases in muscle CSA typically occur during the pubescent period (Morse et al., 2008).

Muscle architectural parameters influence the force-length (torque-angle) and force-velocity (torque-velocity) properties of skeletal muscles. In soccer, the force-length and force-velocity relations are determinants for the ability to kick a ball hard and pass it accurately, for sprinting and jumping, and perturbations of these properties may lead to muscular imbalance and injury (Hoff & Helgerud, 2004). Studies aimed at comparing torque-angle and the torque-velocity properties between children and adults are rare, and virtually non-existent for athletic populations (Barrett & Harrison, 2002; Borges et al., 2003; Marginson & Eston, 2001). Marginson and Eston (2001) compared force-length relations of the knee extensor muscles between children and adults, and reported that this relation was shifted to the right (i.e. longer muscle lengths or more flexed knee angles) for the children compared to the adults. This result was justified by the smaller passive muscle stiffness in the children, and the authors concluded that the force-length relation is affected by chronological age. However, this study did not use any normalization method to adjust for body size differences between the children and the adults. Barret and Harrison (2002) examined the torque-velocity relation in children and adults. They found differences in the absolute torque-velocity relation, and these differences remained even after torques were normalized by CSA and angular velocity by limb length. However, when torques were normalized by MV, the differences disappeared, suggesting that the torque differences between children and adults are due to the muscle size, and not due to changes associated with maturation. Our results partially support this idea, as we observed significant differences between the PUB and POSP athletes for the absolute torque-angle and torque-velocity relations, and for these relations when normalized by body mass (Nm.kg⁻¹), but not when torques were normalized by MV. Nevertheless, we found the normalization by MV inadequate for our data because isometric and dynamics torques relative to MV (Nm.m⁻¹) remained significantly correlated with MV, it was unable to provide a significant allometric exponent for dynamic torque, and the assumption of homogeneity among the exponents was broken (Table 2).

The effect of maturity status on force and torque observed in past studies could be partially explained by applying different methods to assess force/torque, biological maturation, and inappropriate data normalization. A criticism for studies that do not normalize force/torque outcomes is that the methodological approach may not guarantee a fair comparison among athletes at different stages of maturation or with different

body sizes, resulting in selection bias. Thus, the discrepancy between these results could be due to a phenomenon known as the scaling denominator (Bouchant et al., 2011; De Ste Croix et al., 2003; Herzog et al., 2011).

A possible limitation of the present study is that, for the torque-angle relation, participants performed only one maximal voluntary contraction for each of the six different joint angles tested. As a suggestion, future studies could include a prepubescent group of athletes and groups of non-athletes for the varying maturational stages in order to determine the effects of soccer training on the physical development. In addition, measuring MV and physiological CSA through magnetic resonance imaging rather than ultrasound could improve the accuracy and reliability of these measures, resulting in an improved relation among muscle architectural parameters and muscular torques. Finally, measuring muscle activation of agonistic and antagonistic muscle groups could allow to distinguish if changes in muscle force are caused by intrinsic muscular changes or by changes in neural activation.

To conclude, maturity status did not show a significant effect on isometric and dynamic torques (concentric and eccentric) when they were normalized by allometric exponents relative to body mass. The progressive force and torque increases, generally attributed to biological maturation during the transition from child to adulthood, seem to be caused by the effect known as scaling denominator. Muscle architectural variables were not influenced by biological maturation, except for MV.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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