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SPORTS PERFORMANCE



Effect of maturity status on force-velocity relationships in a ballistic lower limb test in high-level soccer players

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ABSTRACT

This study aimed to investigate the effect of maturity status on force-velocity relationships in a ballistic lower limb (BLL) test in high-level soccer adolescents and young adults. The population was 61 adolescents (13.0–17.9 years) and 23 young adults (18.0–26.2 years). Subjects completed the BLL test on a ballistic ergometer equipped with two force plates and a linear encoder. Following Samozino's method, maximal power output (P_{\max}), force (F_0) and velocity (v_0) were determined. An allometric model was applied to P_{\max} and F_0 with body mass (BM) and fat-free mass (FFM). Significant effects of maturity status were found for absolute P_{\max} , F_0 , relative P_{\max} to BM and FFM, relative F_0 to FFM and F_0 allometrically scaled to BM and FFM ($p = 0.02$ to $p < 0.001$; $\eta = 0.10$ to $\eta = 0.49$). There was no significant effect for P_{\max} allometrically scaled to BM and FFM, F_0 relative to BM and v_0 . Body dimensions explain group differences in P_{\max} whereas for F_0 , qualitative factors explain the differences between the groups. As maturity status and body dimensions influence P_{\max} , these factors should be considered when assessing explosive short efforts. This could help to better identify potential athletic talent and adapt training content.

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KEYWORDS

Maturity status;
neuromuscular function;
explosive short performance;
force-velocity profile

Introduction

Soccer is an exhaustive team sport requiring a high level of tactical, technical, and physical ability to succeed. During both training sessions and matches, players engage in a varied combination of explosive and powerful actions at irregular intervals (Stølen et al., 2005). On average, soccer players perform between 1000 and 1400 short actions, with frequent changes every 4 to 6 sec, and high-intensity actions every 70 sec requiring a physiological demand that highly taxes anaerobic and aerobic energy systems (Stølen et al., 2005). These brief maximum-intensity actions, such as sprint accelerations, change of direction and vertical jumps, often immediately precede goals and scoring opportunities in elite-level soccer (Faude et al., 2012), highlighting the importance of explosive short efforts in soccer (Cometti et al., 2001). These actions mainly depend on horizontal/vertical force and velocity production capacities (Samozino et al., 2014) which can be characterized by theoretical maximum force (F_0), velocity (v_0), and power (P_{\max}) obtained from the force-velocity (F-v) relationship. Some studies investigated the performance of adolescents in explosive short efforts (McCunn et al., 2017; Murtagh et al., 2020), whereas other studies have examined the underlying parameters determining the performance of these tasks (power, force and velocity in sprinting or vertical jumping) (Cunha et al., 2017; Fernández-Galván et al., 2022). However, using loaded jumps may not be advisable for paediatric populations due to their potentially poor squatting and landing technique, the risk of overloading the growing spine, and the increased force during landing (Faigenbaum et al., 2009). Young people could also show some difficulty in correctly

performing the loaded jump (probably due to their young age and low training experience) (Fessl et al., 2022) which could influence the proper establishment of their F-v relationship. Therefore, one previous study has focused on the F-v parameters assessed in a ballistic lower limb test (BLL) in young male athletes (C. M. Meylan et al., 2014), but this is the only study involving a young population using this type of ergometer, and there is no information on young high-level soccer players. This is surprising given the importance of explosive short efforts in soccer activity (Cometti et al., 2001; Faude et al., 2012). In fact, muscular power is considered a defining physical characteristic of elite players in soccer and must be trained from the early stages of a player's development. Moreover, the vertical loaded jump and its derivatives (e.g., the BLL test) are commonly used to assess lower limb power due to their simplicity and explosiveness (Cormie et al., 2011; C. M. Meylan et al., 2014). Using the BLL test may provide a reliable and safe method to better understand the mechanistic changes responsible for the increase in power from adolescence to adulthood (Van Praagh & Doré, 2002). This could provide better training information for soccer performance and help to improve the long-term development of the athlete.

The BLL test has been used recently to assess iso-inertial lower limb power in both adults and adolescents (Macchi, Santuz, Hays, Vercruyssen, et al., 2022; C. M. P. Meylan et al., 2015). Compared to the traditional vertical loaded jump, this test is considered safer for young athletes with limited weightlifting experience (Cronin & Henderson, 2004), and the testing time required to assess the F-v profile is relatively short,

consisting of only 8 to 10 trials (Faigenbaum et al., 2003). The ballistic nature of the supine squat allows participants to perform an effort similar to a jump, with concentric contraction only. This allows precise evaluation of the explosive force production capacity of the lower limbs in a single extension movement (Morin & Samozino, 2018). It is then possible to obtain maximal power, force and velocity production capacities of the lower limbs without considering the technical aspects. Moreover, this type of ergometer and most of the kinetic and kinematic variables associated are reliable in both adults and young people as long as a familiarization session has been carried out before (Lindberg et al., 2021; C. M. P. Meylan et al., 2015). Given the significant physiological and morphological changes that occur during youth that can influence force, velocity, and power output (Van Praagh & Doré, 2002), such analysis would provide a safe method to better understand explosive short-performance changes from adolescence to adulthood. For example, increased muscle cross-sectional area with age is likely to influence the force component of power, while greater sarcomere length may enhance velocity capabilities (Van Praagh & Doré, 2002). Other factors such as motor-unit recruitment may affect both aspects of the F-v relationship responsible for power output (Dotan et al., 2012). In this way, C. M. Meylan et al. (2014) have shown that power development was associated with an increase in absolute force and velocity capacity during adolescence in a BLL test. When comparing young athletes, it is recommended to take into account the effect of body dimensions to provide insight into the underlying factors for the changes in the F-v profile. Force and power variables are commonly expressed using ratio scaling, but such scaling is not appropriate to give a dimension-free index. To overcome this, an allometric model must be applied for a more appropriate account of differences in body dimensions (Jaric et al., 2005) since muscle strength or power production capabilities do not increase linearly with increasing body dimensions (Nevill & Holder, 1995).

Finally, in untrained adults, Yamauchi & Ishii (2007) showed that F-v parameters measured on this type of ergometer were correlated with countermovement jump (CMJ) performance. For young soccer players, it would be interesting to know whether F-v parameters obtained from the BLL test are also associated with explosive efforts on the field (such as vertical jumps) (Cometti et al., 2001; Faude et al., 2012). This evaluation could be complementary to the F-v profiling approach and reinforce the importance of using this type of ergometer in young athletes. With the progression of maturity status and consequently specialization in soccer practice, it could be expected that the F-v characteristics assessed on the BLL test would be increasingly less associated with vertical jump performance. The aims of this study were as follows: (i) to investigate the effect of maturity status on F-v relationships using a BLL test in high-level soccer adolescents and young adults; (ii) to analyse the effect of body dimensions (body mass (BM) and fat-free mass (FFM)) using an allometric model applied to F_0 and P_{\max} ; and (iii) to study the magnitude of associations between vertical jumping performance and BLL test according to maturity status. Our hypotheses were as follows: (i) power, force and velocity capacities increase from adolescence to adulthood; (ii) the allometric model reduces the differences

between the groups; and (iii) with advancing maturity status and specialization in soccer practice, the BLL test is not associated with jumping performance.

Methods

Participants

The population was 61 high-level soccer adolescents (range: 13.0–17.9 years) and 23 high-level soccer young adults (range: 18.0–26.2 years) divided into three groups: Mid-PHV ($n = 31$; range: 13.0–16.1 years), Post-PHV ($n = 30$; range: 14.7–17.9 years) and young adults ($n = 23$; range: 18.0–26.2 years). Players were recruited at the training centre of Olympique de Marseille. They trained 4 to 6 times a week, including both technical training and physical conditioning (training session duration: 60–120 minutes).

Inclusion criteria were male, age 12–17 years (included) for adolescent players and age ≥ 18 years for young adults engaged in competitive soccer and physically able to perform the tests. Non-inclusion criteria were previous surgery on the lower limbs or injuries identified in the 3 months preceding the tests. Participants gave their informed consent, and permission was also obtained from the soccer club and parents or legal guardians. The protocol was approved by the national ethical committee of Sport Sciences (CERSTAPS n° IRB00012476–1 May 2022–144).

Procedures

Each subject completed one session of physical testing in February 2022. When the subjects arrived at the laboratory, anthropometric characteristics and maturity status were assessed. The subjects then performed two maximal squat jump (SJ) and CMJ trials. Following this, they completed the BLL test on a ballistic ergometer (Figure 1). Before the physical tests, each subject performed a warm-up consisting of 5 min of cycling at a cadence of 70–80 rpm, three 30-s accelerations between 120 and 130 rpm interspersed with 1 min's active recovery at 60 rpm and some active dynamic stretching. For the BLL test, each subject performed two trials at progressively increasing loads before starting the test.

Measurements

Anthropometry and somatic maturation

Height and sitting height were determined using a stadiometer (0.01 m, The Leicester Height Measure, Tanita Corp., Japan) and BM was obtained using a clinical scale (0.1 kg, Tanita UM-076, Tanita Corp., Japan). Skinfolds at the sub-scapular, bicipital, tricipital and supra-iliac sites were measured to estimate the percentage of whole-body fat using a Harpenden skinfold caliper (Baty International, England). Body fat percentage was determined using the Siri equation (1956) and was adapted for age with reference data from Lohman (Lohman, 1989) for adolescents. FFM was estimated from the percentage of fat mass. Maturity status was estimated through somatic maturation derived from the estimated age at the peak of height velocity (PHV) using the algorithm proposed by Mirwald et al.

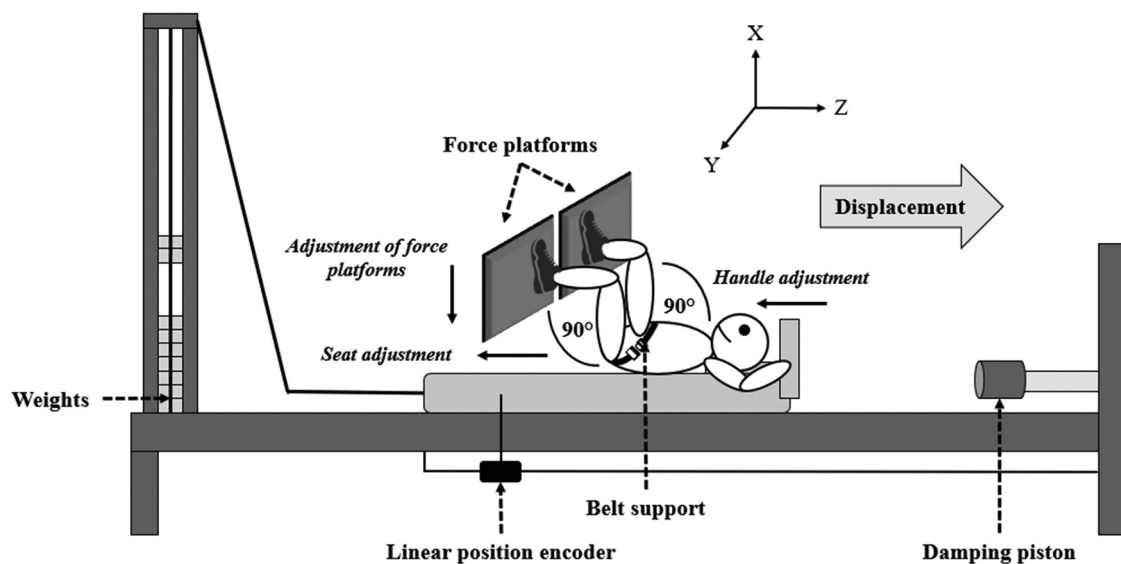


Figure 1. Experimental setup for the ballistic lower limb test adapted and used by permission from Macchi et al (Macchi, Santuz, Hays, Vercruyssen, et al., 2022). Adjustable parameters based on players' body dimensions are shown in *italics*.

(2002). For adolescents, two groups were formed: $-0.5 < \text{Mid-PHV} \leq 0.5$ and $\text{Post-PHV} \geq +0.5$.

Jump tests

The jump tests consisted of two maximal trials of SJ and CMJ, with 1 min of passive rest in between. Participants had to keep their arms forward, look straight ahead at a visual marker on the wall and jump as quickly and as high as possible. For the SJ, participants were required to descend to the lowest point of a jumping position, achieving an angle of around 90° knee flexion. They had to maintain this position for a minimum of 2 s before executing a purely concentric jumping motion. The jump tests were conducted in a random order, recording the best of two attempts for each. In all jumps, participants were advised to take off with fully extended knees and ankles and to land in a similarly extended position. The Optojump photocell system (Microgate, Bolzano, Italy, 1000 Hz) was used to measure the time flight of the jumps, enabling the jump height to be estimated as follows: $9.81 * \text{timeofflight} / 8$ (Bosco et al., 1983).

Ballistic lower limb test

This test has already been described elsewhere (Macchi, Santuz, Hays, Arampatzis, et al., 2022). Briefly, this test consisted of two trials of BLL in a supine position on a frictionless sledge at four relative loads to BM (%) in a randomized order: 0%, 30%, 50% and 70% for players in U14, U15, and U16 and 0%, 40%, 70% and 100% for players in U17 and young adults (Figure 1). For the 0% BM condition, the mass of the unloaded sledge was 52 kg. The starting position was held still for 2–3 s with hip, knee, and ankle joints at 90°. Subjects had to apply their force as quickly as possible on the force plates to achieve the highest velocity at take-off. A trial was not considered if there was the presence of

countermovement or a different distance of push-off (Macchi, Santuz, Hays, Arampatzis, et al., 2022) from previous trials.

Subjects had 30 s of recovery time between trial loads and 120 s between loads. All trials were performed on two force plates (Kistler 9260AA3, 0.5×0.3 m, 2000 Hz). Horizontal displacement over time was recorded with an accuracy of 0.1 cm using a linear encoder attached to the sledge (Micro-Epsilon WDS-3000-P115-SR-U). The players tested in this study were familiarized as they had already performed this test before because it was part of their testing routine during the season (pre- and mid-season).

Allometric model

An allometric model was applied to P_{\max} and F_0 with BM and FFM. BM and FFM were used because both dimensional variables have an impact on power and force production (Sudlow et al., 2024). These two variables are frequently used in the literature to study the effect of body dimensions in young populations and adults (Armstrong & Welsman, 2019; Sudlow et al., 2024; Weber et al., 2006). Using these two variables also allows comparisons to be made with previously reported data and/or the theoretical exponent of BM (0.67) (Jaric et al., 2005). The allometric model was not applied to v_0 as it is known that the maximal velocity of body limbs or velocity of the entire body should not depend of body dimensions (Jaric et al., 2005; C. M. Meylan et al., 2014). The general form of the allometric relationship is given by Equation (1) (Nevill & Holder, 1995):

$$Y = a.X^b \quad (1)$$

Where Y is the performance variable, a is the coefficient of proportionality, X is the variable of dimension, and b is the exponent. The determination of the coefficients a and b is enabled using the method of least squares after applying

a logarithmic transformation to the data. Equation 1 then becomes:

$$\log(Y) = \log(a) + b.\log(X) \quad (2)$$

Data analysis

Data analysis was performed using a custom Matlab routine (Matworks Inc, Novi, USA, R2019a). The initiation of the push-off was determined by identifying the point of inflexion on the force curve (threshold: 5N), whereas the end of the push-off was established based on the point when the normal component of the ground reaction force reached zero. For each trial at each load condition, the mean force, velocity and power output were obtained. From these mean values, linear F-v slopes were determined by least-squares linear regression and extrapolated to determine the F_0 and v_0 values that correspond to the intersections with the force and velocity axis, respectively (Macchi, Santuz, Hays, Vercruyssen, et al., 2022; Samozino et al., 2012). From the velocity-power polynomial relationship, P_{\max} was determined (Samozino et al., 2012). A selection was made for each participant among the 8-dynamic push-offs so that the most accurate linear F-v relationship could be obtained (Macchi, Santuz, Hays, Arampatzis, et al., 2022) (as a potential hip lift, slight countermovement, different distance of push-off or non-maximal trial could distort linearity). Using the coefficient of determination (R^2), each linear relationship was evaluated. The F-v-power relationships were fitted for both legs. Following Samozino et al. (2012), the slope of the F-v relationship was computed (S_{FV}). The following explosive strength parameters were determined: time to maximal force (F_{\max}) and rate of force development (RFD) over the time-interval of 0–75 ms, at load 0% of BM.

Statistics

All data are presented as mean \pm standard deviation. A one-way analysis of variance (ANOVA) according to maturity status (Mid-PHV, Post-PHV, young adult) was performed on anthropometric, F-v and explosive strength parameters. Each ANOVA was performed after checking for distribution normality with Shapiro-Wilk's test and homogeneity of variance with Levene's test. If not met, a Kruskal–Wallis test was performed. If a main maturity status effect was found, pairwise comparisons using Tukey post hoc tests were used to determine exactly which groups were different. For Kruskal–Wallis's test, pairwise

comparisons with Dunn's post hoc test were used (Bonferroni p-value adjustment). Eta-squared (η) was used for effect size calculations in ANOVA. For the Kruskal–Wallis test, the effect size was computed as follows:

$$\eta^2 = \frac{H}{N - 1}$$

where H is the value obtained in the Kruskal–Wallis test and N the total number of observations. The effect sizes are considered small, medium, and large effects if the calculated η are approximately equal to 0.01, 0.06, and 0.14, respectively (Lakens, 2013). Correlations were performed to assess the associations between jump performance (SJ and CMJ) and F-v parameters (P_{\max} , F_0 and v_0) obtained during the BLL test in each maturity group. Pearson product-moment correlation coefficients (r) were used. If the normality of the data was not respected, Spearman's rho (ρ) was used. Qualitative interpretations of the correlation coefficients were as follows: trivial ($r < 0.1$), small ($r = 0.1–0.3$), moderate ($r = 0.3–0.5$), large ($r = 0.5–0.7$), very large ($r = 0.7–0.9$), and nearly perfect ($r > 0.9$) (Hopkins et al., 2009). Statistical analyses were performed using SPSS (IBM SPSS, v26.0). The α risk was set at 5% ($p < .05$).

Results

Anthropometry, body composition and somatic maturation

Table 1 presents descriptive data, group and post-hoc pairwise comparisons according to maturity status for the anthropometric characteristics, body composition and somatic maturation. There was a significant main effect of maturity status for all anthropometric and body composition parameters ($p < 0.001$; $\eta \geq 0.17$).

Absolute, relative, allometrically scaled F-v and explosive strength parameters

The mean \pm SD [min–max] for R^2 value was: 0.86 ± 0.05 [0.80–0.99]; 0.88 ± 0.05 [0.80–0.99] and 0.90 ± 0.06 [0.81–0.99] for Mid-PHV, Post-PHV and young adults, respectively. Table 2 presents descriptive data and one-way analysis of variance for absolute, relative, allometrically scaled F-v and explosive strength parameters according to maturity status. Significant main effects of maturity status were found for absolute P_{\max} , F_0 , relative P_{\max} to BM and FFM, relative F_0 to FFM and F_0 allometrically scaled to BM and FFM ($p = 0.02$ to $p < 0.001$; $\eta = 0.10$ to $\eta = 0.49$) (Figures 2 and 3). There

Table 1. Comparisons of anthropometry, body composition and somatic maturation according to maturity status.

Variables (mean \pm SD)	Mid-PHV (n = 31)	Post-PHV (n = 30)	Young adults (n = 23)	p value	η
Age (years)	14.6 \pm 1.9 ^{a,b}	16.4 \pm 0.8 ^b	19.2 \pm 1.8	<0.001	0.81
BM (kg)	56.9 \pm 6.9 ^{a,b}	66.6 \pm 6.6 ^b	72.4 \pm 7.2	<0.001	0.47
Height (m)	1.68 \pm 0.5 ^{a,b}	1.77 \pm 0.6	1.78 \pm 0.6	<0.001	0.39
BMI (kg.m ⁻²) (Faude et al., 2012)	20.1 \pm 1.7 ^{a,b}	21.4 \pm 1.7 ^b	22.9 \pm 1.7	<0.001	0.29
SH (m)	0.83 \pm 0.3 ^{a,b}	0.89 \pm 0.4 ^b	0.91 \pm 0.3	<0.001	0.52
Whole-body fat (%)	12.7 \pm 3.0 ^a	14.8 \pm 2.6 ^b	12.1 \pm 1.8	<0.001	0.17
FFM (kg)	49.5 \pm 5.0 ^{a,b}	56.7 \pm 5.1 ^b	63.5 \pm 6.5	<0.001	0.51
Maturity-Offset (years)	+0.1 \pm 0.5	+1.7 \pm 0.6	+3.6 \pm 1.2	-	-

Mid-PHV, pubertal; Post-PHV, post-pubertal; BM, body mass; BMI, body mass index; SH, sitting height; FFM, fat-free mass. The letters a and b indicate a significant difference with Post-PHV and young adults, respectively.

Table 2. Descriptive data and one-way analysis of variance for absolute, relative, allometrically scaled F-v and explosive strength parameters according to maturity status.

Variables	Descriptive data (mean \pm SD)			Maturity status effect	
	Mid-PHV (n = 31)	Post-PHV (n = 30)	Young adults (n = 23)	p value	η^2
P_{\max} (W)	1010.1 \pm 265.2 ^{a,b}	1369.5 \pm 346.7 ^b	1626.7 \pm 389.6	<0.001	0.37
P_{\max}/BM (W.kg ⁻¹)	17.9 \pm 4.6 ^b	20.4 \pm 4.4	22.5 \pm 4.8	0.002	0.14
$P_{\max}/BM^{1.41}$	3.4 \pm 0.9	3.7 \pm 0.8	3.9 \pm 0.8	0.15	0.05
P_{\max}/FFM (W.kg ⁻¹)	20.5 \pm 5.2 ^{a,b}	24.1 \pm 5.3	25.5 \pm 5.3	0.002	0.14
$P_{\max}/FFM^{1.51}$	2.8 \pm 0.7	3.1 \pm 0.7	3.1 \pm 0.6	0.26	0.03
F_0 (N)	1321.6 \pm 197.7 ^{a,b}	1647.2 \pm 198.3 ^b	1819.9 \pm 248.3	<0.001	0.49
F_0/BM (N.kg ⁻¹)	23.5 \pm 3.5	24.8 \pm 3.0	25.3 \pm 2.9	0.10	0.06
$F_0/BM^{0.91}$	33.6 \pm 4.8 ^b	36.2 \pm 4.2	37.0 \pm 4.2	0.014	0.10
F_0/FFM (N.kg ⁻¹)	27.0 \pm 3.6 ^a	29.2 \pm 3.5	28.6 \pm 2.8	0.02	0.10
$F_0/FFM^{0.97}$	30.1 \pm 4.0 ^a	32.9 \pm 3.9	32.4 \pm 3.2	0.011	0.11
v_0 (m.s ⁻¹)	3.1 \pm 1.0	3.3 \pm 0.8	3.6 \pm 0.8	0.07	0.06
S_{FV} (N.s.m ⁻¹ .kg ⁻¹)	-8.4 \pm 3.3	-7.9 \pm 2.3	-7.4 \pm 2.0	0.60	0.01
Time to F_{\max} 0% BM (s)	0.31 \pm 0.05 ^b	0.29 \pm 0.04	0.28 \pm 0.04	0.011	0.11
RFD 0–75 ms 0% BM (N.s ⁻¹)	3597.2 \pm 2037.8 ^{a,b}	5375.4 \pm 2338.3	6669.6 \pm 3248.8	<0.001	0.19

Mid-PHV, pubertal; Post-PHV, post-pubertal; P_{\max} , maximal power output; BM, body mass; FFM, fat-free mass; F_0 , theoretical maximal force; v_0 , theoretical maximum velocity; S_{FV} , force-velocity slope; F_{\max} , maximal force; RFD, rate of force development. The letters a and b indicate a significant difference with Post-PHV and young adults, respectively.

was no significant effect for P_{\max} allometrically scaled to BM and FFM, F_0 relative to BM, S_{FV}/BM (Figures 2, 3 and 4) and v_0 . Post-hoc pairwise comparisons according to maturity status for relative P_{\max} to BM showed that Mid-PHV was significantly different to young adults ($p = 0.001$). There were no significant differences between the Mid-PHV and Post-PHV groups. A significant main effect of maturity status was found for time to F_{\max} ($p = 0.011$; $\eta = 0.11$) and RFD 0–75 ms ($p < 0.001$; $\eta = 0.19$) at load 0% of BM (Figure 5).

Jump tests

There was no correlation between jump performance in SJ and CMJ and F-v parameters for Post-PHV and adults. Only significant and moderate associations ($p = 0.01$; $r = 0.44$ to 0.48) were found for Mid-PHV between absolute F_0 and jump performance in SJ and CMJ.

Discussion

The main results of this study showed that absolute P_{\max} and F_0 increase significantly as players become more mature, whereas no change in v_0 and F-v slope was observed. These group differences in P_{\max} are mainly explained by body dimensions. Indeed, after applying an allometric model to P_{\max} with BM and FFM, group differences disappeared. This was not the case for F_0 , since the differences between groups persisted even after applying an allometric model with BM and FFM. Therefore, maturation-related changes in qualitative factors, i.e., factors that do not depend on body dimensions, may explain the differences that remain between groups. SJ and CMJ performance were associated with absolute F_0 obtained from the BLL test in the Mid-PHV group, whereas there was no association in other groups.

It is difficult to compare our data with the literature, as few studies have investigated F-v relationships in the BLL test with young populations. Only C. M. Meylan et al. (2014) reported data on a similar ergometer in young athletes (P_{\max} : 400 \pm 101 W vs 1010 \pm 265 W; F_0 : 1090 \pm 200 N vs 1321 \pm 197 N; v_0 : 1.43 \pm 0.23 m.s⁻¹ vs 3.1 \pm 1.0 m.s⁻¹ for Mid-PHV and P_{\max} : 567 \pm 102 W vs 1369 \pm 346 W; F_0 : 1220 \pm 170 N vs 1647 \pm 198 N; v_0 : 1.98 \pm

0.43 m.s⁻¹ vs 3.3 \pm 0.8 m.s⁻¹ for Post-PHV). Our values were higher for the two maturity status groups (Mid-PHV and Post-PHV). This could be due to population differences since our players were in a training centre (high-level) and were more mature and older. It is known that when studying the effect of maturity status on physiological performance, it is crucial to employ suitable methods to eliminate the impact of body dimensions. C. M. Meylan et al. (2014) showed that after applying an allometric model to P_{\max} and F_{\max} , differences between the groups persisted. They suggested that the remaining difference could be explained by maturation-related changes in qualitative neuromuscular factors. Our results are in agreement for F_0 but not for P_{\max} since no further differences were observed between groups after the application of the allometric model. This could be explained by the dimension variable chosen (BM instead of FFM) (Loftin et al., 2016). Although there are differences between the protocols (allometric method, population, test performed), our results are consistent with previous literature on the fact that differences between groups are reduced or removed after the application of an allometric model (Cunha et al., 2017; Fernández-Galván et al., 2022; Thompson et al., 2010). Our BM exponents can only be compared with those of C. M. Meylan et al. (2014) who have reported quite low exponents for P_{\max} (0.85 vs. 1.41) and F_{\max} (0.56 vs. 0.91). Moreover, all BM exponents differed from the theoretical BM exponent of 0.67 proposed previously (Jaric et al., 2005). This could be due to the differences in ergometers, and the population studied since allometric exponents are known to be sample and test-specific (Jaric et al., 2005).

Body dimensions, which increase with maturity status, contribute significantly to the improved capacity to produce force and power in ballistic movement in youth (Van Praagh & Doré, 2002). Then, the ability to generate maximal force and power is influenced by a series of quantitative morphological and structural factors, such as muscle cross-sectional area and physiological cross-sectional area, muscle volume and thickness, pennation angle and fascicle length (Kanehisa et al., 1995; Kawakami et al., 1993, 1995, 2000; Tonson et al., 2008; Tumkur Anil Kumar et al., 2021). It also seems important to note that such morphological and structural changes with maturity status are linked to the

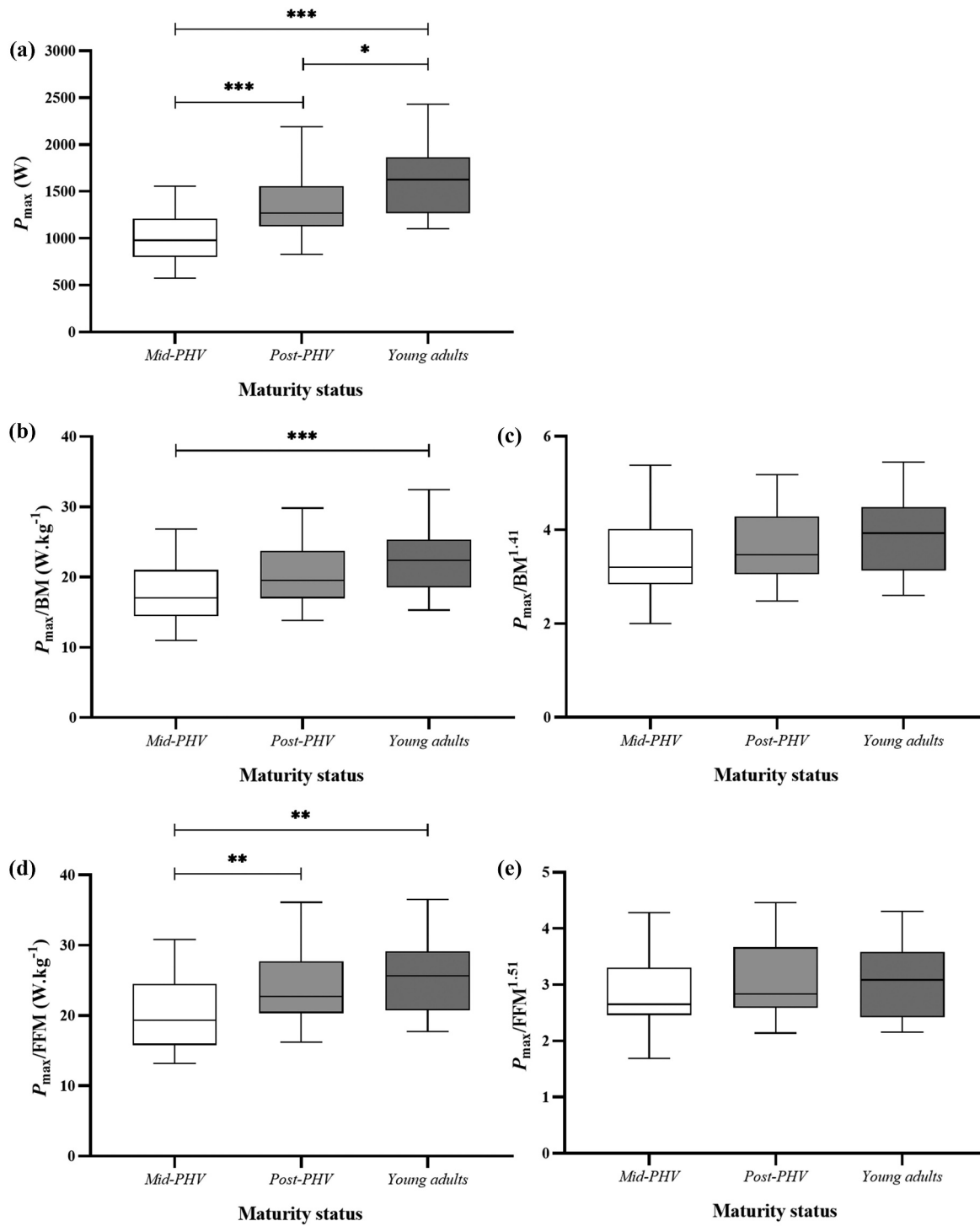


Figure 2. One-way analysis of variance for absolute P_{\max} (a), relative P_{\max} to BM (b), relative P_{\max} to FFM (c), P_{\max} allometrically scaled to BM (d), and, P_{\max} allometrically scaled to FFM (e) according to maturity status. Post hoc results are represented between each group. Mid-PHV, pubertal; Post-PHV, post-pubertal; P_{\max} , maximal power output; BM, body mass; FFM, fat-free-mass. *** $p = .001$; ** $p = .01$; * $p = .05$.

progressive increase in circulating androgen hormones starting at puberty (Viru et al., 1999). Our results showed that there were still significant differences between the groups for P_{\max} relative to BM and FFM. However, given that there were no longer any significant differences in P_{\max} between groups after the application of the allometric model, quantitative factors seem to explain the differences observed. Previous research has shown that these quantitative factors undergo growth and maturity-related

changes as children move into adolescence, mainly between the ages of 13 and 15 in boys (Tumkur Anil Kumar et al., 2021; Viru et al., 1999) which is consistent with the increase in absolute P_{\max} between groups. The increase in body dimensions could also be due to other factors such as the increased training load with age.

Conversely, there were still significant differences between groups for F_0 allometrically scaled with BM (Mid-PHV vs. young

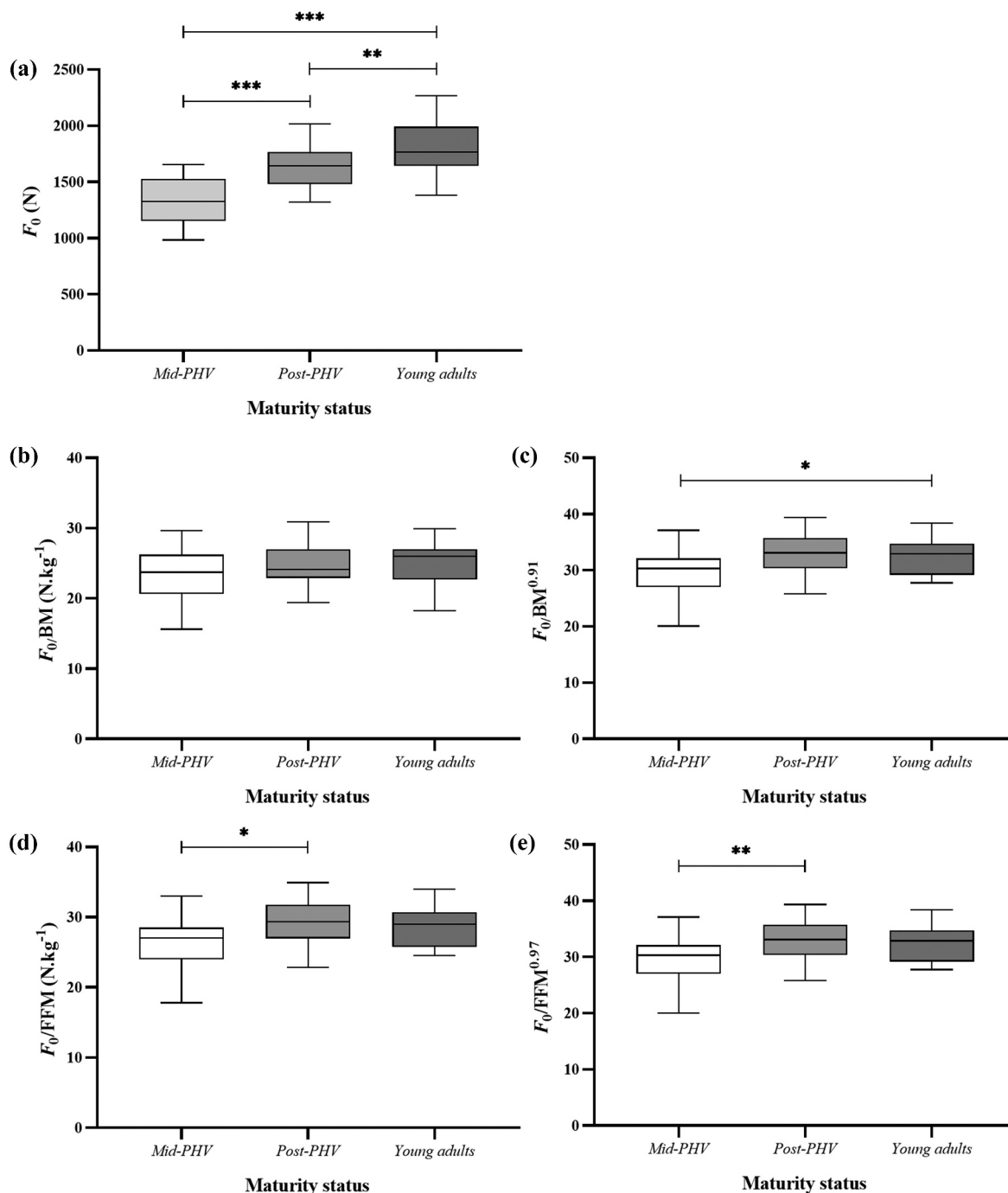


Figure 3. One-way analysis of variance for absolute F_0 (a), relative F_0 to BM (b), relative F_0 to FFM (c), F_0 allometrically scaled to BM (d), and F_0 allometrically scaled to FFM (e) according to maturity status. Post hoc results are represented between each group. Mid-PHV, pubertal; Post-PHV, post-pubertal; F_0 , theoretical maximal force; BM, body mass; FFM, fat-free-mass. *** $p = .001$; ** $p = .01$; * $p = .05$.

adults) and FFM (Mid-PHV vs. Post-PHV). This means that even when the effect of body dimensions was taken into account, the differences persisted. Hence, qualitative factors, i.e., factors that do not depend on body dimensions, may explain the remaining differences between groups. According to previous research, growth and maturation underpin a significant number of qualitative changes in the neuromuscular system: muscle activation of motor units, rate of force development, reduced electromechanical delay, increased muscle pre-activation, reduced agonist – antagonist co-contraction, and improved

stretch reflex control and conduction velocity (Grosset et al., 2008; Koh & Eyre, 1988; Lambertz et al., 2003; Lazaridis et al., 2010; Seger & Thorstensson, 2000; Tumkur Anil Kumar et al., 2021; Van Praagh & Doré, 2002). These attributes improve as youth transition from childhood through adolescence and into adulthood and are closely associated with explosive short-effort performance (Tumkur Anil Kumar et al., 2021). This is supported by the significant decrease (time to F_{max} at load 0% BM) and increase (RFD 0–75 ms at load 0% BM) in explosive strength parameters with maturity status (Figure 5). This means

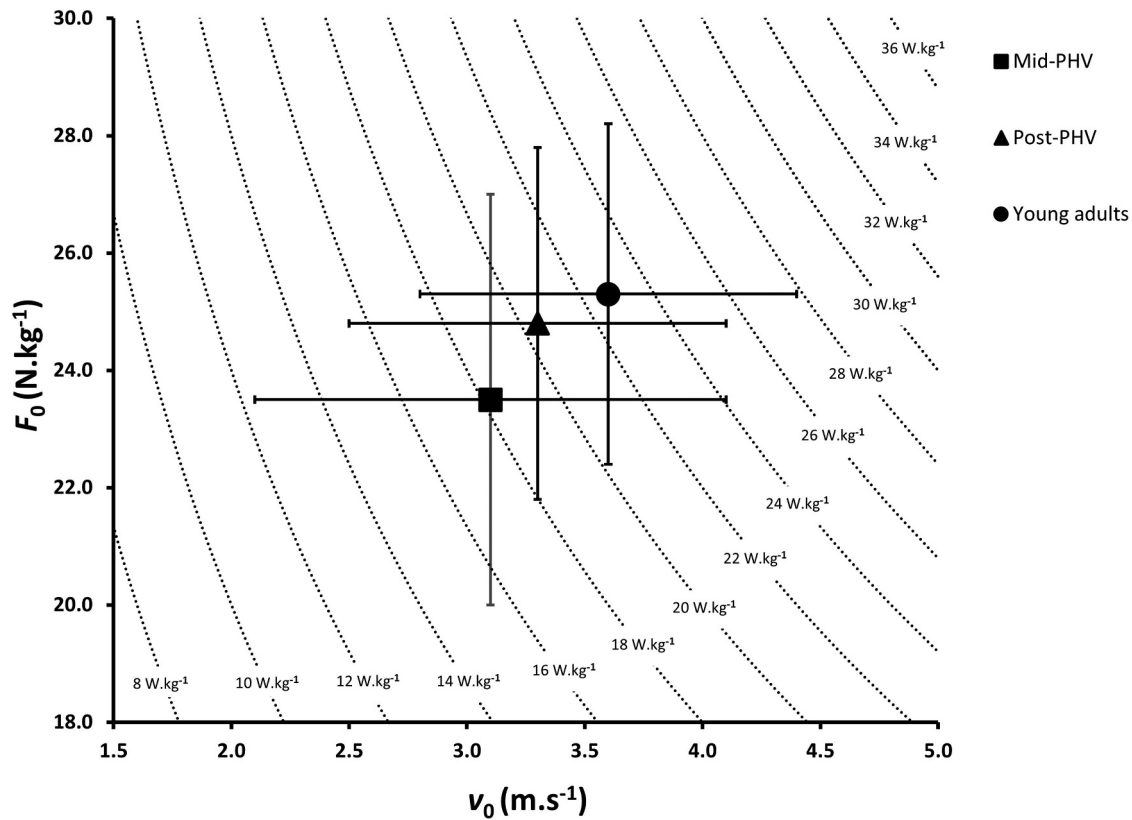


Figure 4. Maximal power output (P_{\max}) according to maturity status. Each dotted line represents a value of P_{\max} for a given value of theoretical maximal force relative to BM (F_0) and theoretical maximal velocity (v_0). Standard deviations are represented for both F_0 and v_0 and each group. Mid-PHV, pubertal; Post-PHV, post-pubertal.

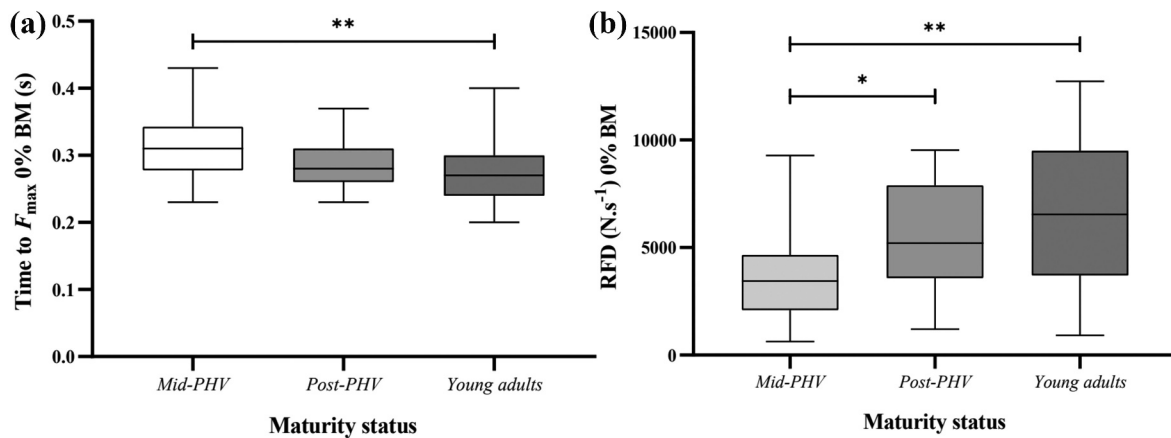


Figure 5. One-way analysis of variance of explosive strength parameters (time to maximal force (F_{\max}) (a) and rate of force development (RFD) over the time-interval of 0–75 ms (b) at load 0% BM according to maturity status. Post hoc results are represented between each group. Mid-PHV, pubertal; Post-PHV, post-pubertal; RFD, rate of force development; BM, body mass. *** $p = .001$; ** $p = .01$; * $p = .05$.

that explosiveness qualities, i.e., the ability to produce maximum force in a very short time (≈ 0.3 s), improve with maturity status (Van Praagh & Doré, 2002). This is consistent with the multiple changes that occur from adolescence to adulthood in the neuromuscular system and the positive effect of soccer training due to increased training load and the specificity of the activity which relies heavily on explosive and powerful actions (Stølen et al., 2005). It is also possible that the remaining differences observed in F_0 are explained by “adolescent awkwardness” (Philippaerts et al., 2006). This refers to a disruption

in motor coordination resulting from the differential timing of growth in the legs and trunk. This phenomenon generally appears around PHV, which is consistent with the differences observed between Mid-PHV and Post-PHV or young adults.

Concerning v_0 , the results of this study showed no differences between groups. It could be explained by the fact that neuronal adaptations, influencing v_0 production (Grosset et al., 2008; Koh & Eyre, 1988; Lambert et al., 2003; Lazaridis et al., 2010; Seger & Thorstensson, 2000; Tumkur Anil Kumar et al., 2021; Van Praagh & Doré, 2002) appeared mainly before PHV

(Tumkur Anil Kumar et al., 2021). For adolescents, the v_0 values are slightly higher than those reported by C. M. Meylan et al. (2014) which was expected since it has been previously noted that the utilization of this ergometer resulted in higher extrapolated v_0 values (Macchi, Santuz, Hays, Vercruyssen, et al., 2022). For young adults, our values are consistent with those reported by Macchi, Santuz, Hays, Arampatzis, et al. (2022). ($4.7 \pm 0.8 \text{ m.s}^{-1}$ [$4.0\text{--}6.4 \text{ m.s}^{-1}$]) and other adult populations (Rivière et al., 2023; Yamauchi & Ishii, 2007). S_{FV} reflects the athlete's balance between force and velocity capabilities. There were also no differences between groups in the orientation of the F-v profile. This is noticeable with the concomitant and progressive slight increases in velocity and relative force to BM with maturity status (Figure 4). These non-significant increases in both relative F_0 to BM and v_0 explain why the F-v slope was not modified but resulting in increased power production from Mid-PHV to young adults. Concerning vertical jump performance and F-v power parameters, Yamauchi & Ishii (2007) examined these associations in 67 untrained male and female subjects. They reported that absolute F-v parameters were positively correlated with jump performance, whereas, when F_{\max} and P_{\max} were normalized to BM, no correlation was found. This is partially in line with the results of our study as absolute F_0 was positively associated with SJ and CMJ performance in Mid-PHV, but not P_{\max} . To the best of our knowledge, this is the first study to find associations between F-v parameters obtained from the BLL test and vertical jump performance in trained soccer adolescents. It is consistent to observe a significant link between these tests since both tests are oriented on the same axis and require the athlete to produce maximum concentric force in the lower limbs. However, as expected, these associations were moderate and concerned only Mid-PHV. This may be partly due to the specialization of soccer. The more specialized players are in their discipline, the more neuromuscular qualities (power, force, velocity) are specific to the discipline. In the Mid-PHV group, because of this lower level of sports specialization, the force qualities in the BLL test are more transferable to the SJ and CMJ, which is interesting given the risk of using loaded vertical jumps in this population. Then, the results of this study highlight the importance of using both types of tests to assess power, force and velocity production capacities in young footballers. Compared with traditional vertical jump tests, the BLL test has the advantage of allowing the participant to perform a maximum concentric effort in a highly standardized position. This allows a precise evaluation of the explosive short-performance capacity of the lower limbs based on several extension movements under different resistance conditions (Morin & Samozino, 2018). It is then possible to obtain F-v-power-velocity relationships of the lower limbs while minimizing the technical influences.

This study presents some potential limitations. Firstly, it has been previously noted that the utilization of this ergometer resulted in higher extrapolated v_0 values when compared to the classic vertical SJ (Macchi, Santuz, Hays, Vercruyssen, et al., 2022). Yet, several studies have reported a high level of repeatability for all F-v parameters (Lindberg et al., 2021; C. M. P. Meylan et al., 2015) when using ergometers similar to ours, due to the highly standardized position (Avis et al., 1985). Secondly, the BLL test lacks specificity with the nature of the

actions required in soccer, as the supine squat position is absent from the activity. However, the previous results reported and also a part of the results of this study support the fact that, in trained adolescents and untrained adults (Yamauchi & Ishii, 2007) performance on this type of test is associated with performance during explosive short efforts (SJ and CMJ), which is closer to the reality of the soccer activity. Moreover, the great advantage of using this ergometer is its safety and ability to limit variations in athletes who are more fragile and less experienced such as children and adolescents. Finally, this study lacks control over the training background of each group (training "age"). This could confuse the maturity status effect since the training load increases from category to category and this could have an impact on power, force and velocity production capacities.

Practical applications

Given that maturity status influences the ability to produce maximal power output, it is important to consider this factor when assessing explosive short efforts such as the BLL test. This could help to better identify potential athletic talent and adapt training content. Practitioners should also not compare athletes of different maturity status with the assumption that using ratio scaling BM or FFM accounts for all maturity status effects on force production as qualitative factors were also responsible for the differences between groups. Although the BLL test is relevant for assessing the neuromuscular qualities of the lower limbs, its use may not be as relevant with advances in soccer specificity and maturity status. The F-v relationship is a useful tool for examining the specific adaptations in force and velocity resulting from different loading and subsequent training velocities. For future research, it would be beneficial to explore the effectiveness of different training programmes on the F-v-power profile of young athletes during BLL.

Conclusions

In conclusion, absolute P_{\max} and F_0 increase as players become more mature without a significant increase in velocity production. Body dimensions, which increase with maturity status, explain group differences in P_{\max} . For F_0 , qualitative factors, independently of body dimensions, explain the differences between the groups. Indeed, explosive strength parameters increase significantly with maturity status. Vertical jump performance was only moderately associated with absolute F_0 obtained from the BLL test in the Mid-PHV group.

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Data availability statement

Data described in the manuscript will be made available upon reasonable request to the corresponding author.

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