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MOVEMENT COMPETENCY AND MEASURES OF ISOMETRIC AND DYNAMIC STRENGTH AND POWER IN BOYS OF DIFFERENT MATURITY STATUS

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ABSTRACT

An understanding of how movement competency, strength, and power interacts with natural growth and maturation is required in order to determine meaningful changes with developing athletes. Isometric and dynamic testing in youth athletes provide insight into the natural development of the force-velocity (F-V) spectrum. Two-hundred and six young male athletes, aged 9-17 years of age were grouped according to stage of maturation based on their maturity offset which was determined as number of years from peak height velocity (PHV). All participants performed the back-squat assessment (BSA), isometric mid-thigh pull (IMTP), countermovement jump (CMJ) and squat jump (SJ) tests. Absolute and scaled force-time variables were collected from the IMTP, CMJ, and SJ. No significant differences were observed between maturational groups for squat movement competency ($p > 0.05$). One-way ANOVA with Bonferroni post-hoc analysis revealed that increasing maturity led to significant, moderate to large increases in allometrically scaled peak force (PF_{allo}) for all tests ($p < 0.05$). Multiple stepwise linear regression models revealed IMTP PF_{allo} significantly predicted 34.8% and 41.3% of variance in SJ and CMJ jump height, respectively ($p < 0.05$). Natural growth and maturation induces positive adaptations to movement competency as well as isometric and dynamic strength and power. Trends from the IMTP, SJ, and CMJ tests indicate the largest differences in strength and power may occur around the adolescent growth spurt despite the large variation in rates of change within the circa-PHV group.

Key words: Growth, maturation, countermovement, squat, jump

INTRODUCTION

Position statements on the long-term athletic development of youth highlight the importance of movement competency, strength, and power for young athletes competing in sport [1,2]. The natural development of such qualities has been reported to typically increase in a non-linear fashion with advancing growth and maturation [3-6]. Additionally, maturation has been purported to be a key determinant for improved overall athleticism in young males for many sports [6-9]. In the absence of physical training, the greatest improvements for strength and power arise during adolescence due to natural physical and physiological changes which lead to increased muscle mass and force producing capabilities [4,10]. As a result, boys that mature earlier than their age-group peers gain both a physical advantage in sport and are more likely to be selected in talent-identification processes over later maturing individuals [11]. Therefore, an understanding of how movement competency, strength, and power interacts with natural growth and maturation is required in order to determine meaningful changes with developing athletes.

Studies comparing youth athletes commonly evaluate groups by chronological age which can be a limitation when interpreting athletic performance [12-14]. Because the timing of growth and maturation is highly individualized, large discrepancies in size and strength can arise in youth within the same chronological age [13]. As such, evaluating young athletes based on chronological age is likely to advantage mature children because of their size advantage during tests for movement competency as well as isometric and dynamic force production. Studies that examine developmental data by grouping athletes according to biological maturity provide more meaningful insights [15].

Movement competency reflects the proficiency displayed by an individual during goal-directed movements and this ability has been cited as an underlying determinant for athletic performance in youth athletes [3,16]. Previous literature comparing differences between children and adolescents report that more developed individuals generally display greater performance in movement competency, strength, and power tests [4,10,12,17,18]. When comparing squat movement competency between untrained pre- and post-peak height velocity (PHV) males, Dobbs et al. [17] reported more mature boys had greater levels of movement competency than their less mature counterparts. Maturation enhances movement competency due to a more developed neuromuscular system which leads to greater kinesthetic awareness during athletic movements [16]. The onset of puberty also brings about increased physical size and muscle mass, which enable the greater absolute strength typically seen in adolescents [1,4].

Isometric and dynamic testing in youth athletes provide insight into the natural development across the force-velocity (F-V) spectrum. Determining maximal strength requires an isometric contraction with maximal force with the absence of velocity. Literature on isometric force production has reported that more mature athletes tend to display greater absolute strength than younger athletes primarily due to increased size [4,5,10,19]. Allometric scaling provides a normalized methodological approach for performance tests [20] and has been previously used in measurements of full body strength for youth of different body size [21]. Brownlee et al. [21] reported significant increases in strength with maturity between pre-, mid-, and post-PHV youth soccer players, indicating that maturation likely improves force producing capabilities even when data are controlled for body mass. Despite increases in body mass, maturation appears to also improve movement speed and contraction velocity in male youth which contributes to greater power outputs [19,22]. Across different team sports, dynamic tests such as the 30 m sprints, countermovement jump (CMJ), and standing long jump have displayed that more mature individuals perform better than less mature individuals [6,11,13,23]. Yet, the kinetic strategy used to outperform less mature individuals is unknown.

Existing data investigating differences between pre- and post- PHV athletes often use field-based or laboratory-controlled tests which only provide absolute measures of strength and power. Data from field-based tests (e.g. 1RM or vertical jumps) are practical for coaches; however, they provide little insight into the mechanical variables which might explain increases in strength and power performance. Alternatively, laboratory-based isokinetic strength testing provides kinetic data, but generally has limited external validity with protocols limited to single-joint movements [22]. Few studies have assessed force-time variables across multiple strength and power tests that span the force-velocity spectrum within youth populations. Such data could help determine specific force-time variables that drive athletic performance in youth populations at different stages of maturity and identify those variables that could be targeted synergistically with maturation to more effectively enhance athleticism.

Therefore, the main aim of the present study was to examine differences in movement competency and force-time variables with a range of strength and power tests both between and within cohorts of pre-, circa-, and post-PHV male athletes. A secondary aim was to determine the predictive ability of various force-time variables on squat jump (SJ) and countermovement jump (CMJ) height. It was hypothesized that movement competency, strength, and power would improve with advanced maturity; while jump height would be driven by kinetic variables related to absolute force production and velocity, regardless of maturity status.

MATERIALS & METHODS

Participants

Two-hundred and six young male cricketers, aged 9-17 years at a first-class county cricket club academy in the United Kingdom agreed to participate in the study. No participants had previous experience with strength and conditioning training, screening, or testing prior to the study. Biological maturity status and anthropometric measures are displayed in *Table 1*. Players were grouped into discrete bands according to their stage of maturation based on their maturity offset [15] which was determined as number of years from peak height velocity (PHV) according to the following thresholds: pre- PHV= < -1.0; circa- PHV= -0.5 to 0.5; and post- PHV= > 1.0. Participants who recorded a maturity offset between -1 and -0.5 and 0.5 to 1.0 were subsequently removed from the data set to account for the ~6 month reported error in the regression equation [15]; therefore, the final sample consisted of 206 players (n = 130 pre-PHV, n = 33 circa-PHV, and n = 43 post-PHV). No injuries were reported during testing and all participants were informed of the risks and benefits of taking part in the study. Parental consent and participant assent were obtained following ethical approval from the Cardiff Metropolitan University research ethics committee in accordance with the Declaration of Helsinki.

Study design

This study used a cross-sectional design to determine differences in movement competency, isometric and dynamic strength and power in young male athletes. Participants were classified into one of three maturational groups; pre- PHV, circa- PHV, and post- PHV.

Procedures

Back squat assessment (BSA)

During the BSA, participants were instructed to perform ten continuous squat repetitions in place with a wooden dowel on their back as per previously published guidelines [24]. Participants were instructed to position their feet slightly wider than hip-width and to descend until thighs were parallel to the ground. Aside from the standardized script proposed by Myer and colleagues [24], no other verbal cues or advice were given to participants before or during the testing sessions. All ten repetitions were recorded at 30 f/s using two 2D high definition cameras (Apple iPad, California, USA) positioned at a height of 0.70 m and a distance of 5 m from the center of the capture area in both frontal and sagittal planes. Scoring of BSA performance was conducted retrospectively by the investigator using video analyses. The BSA is scored using a 10-point criteria, with one point given for each technical fault [24]. The 10-point criteria consisted of: head position, thoracic position, trunk position, hip position, frontal knee position, tibial progression angle, foot position, descent, depth, and ascent. During the scoring process, each of the 10 criteria were analyzed and a deficit was scored if present during two or more repetitions. Total number of deficits are tallied to provide a total score, with higher total scores indicative of poorer squat technique. Acceptable intra-rater reliability has been previously reported for the BSA in youth athletes [17].

Isometric mid-thigh pull

The isometric mid-thigh pull (IMTP) test was performed on a custom built IMTP testing device using dual Kistler force plates sampling at a frequency of 1000 Hz (type 9287BA, Kistler Instruments AG, Winterthur, Switzerland). In line with previous research, participants were positioned where: feet were hip-width apart, the bar was positioned at mid-thigh, the torso was upright with a neutral spine, hand straps were wrapped around the bar at hip-width, and knee and hip angles were approximately 140° [25,26]. The customized IMTP rig allowed for incremental bar height adjustments of 1 cm to accommodate athletes of different leg length. Once in position, participants were instructed to remove slack from the bar without applying any force into the ground [25]. All participants received the same instructions, "*pull as hard and as fast as you can in 3, 2, 1, go*". Following familiarization, three maximal effort trials were recorded from each participant with a minimum of 90 seconds rest between each trial for recovery. Each trial was collected for eight seconds, which included a three second countdown and the participants pulling on the bar for five seconds. During the three second countdown, participants were instructed to remain still to optimize stabilization of body weight in order to identify the initiation of the pull. Trials were discounted if participants were unable to remain still or if a countermovement prior to the pull was displayed within the force tracing. All trials and data were analysed on a customized IMTP LabView program. Force-time variables calculated from the customized software included: absolute peak force (PF_{abs}), allometric scaling ($N/kg^{0.67}$) of peak force (PF_{allo}) [20], time to peak force (tPF), peak rate of force development (PRFD), relative peak rate of force development ($PRFD_{rel}$), peak force at time periods of 0-50 ms (PF50), 0-90 ms (PF90), 0-150 ms (PF150), 0-200 ms (PF200), and 0-250 ms (PF250). Acceptable within- and between-session reliability has previously been reported for this IMTP protocol using young athletes [27].

Squat jump

The squat jump (SJ) test was recorded on an AMTI force plate with a sampling rate of 1000 Hz (Accupower, AMTI, Boston, MA, USA). All data were processed using a Butterworth filter. Participants were required to assume a squat position with 90° of knee flexion [28,29] which was visually observed by the researcher. Once in the squat position, participants were instructed to remain still for three seconds, keep hands on hips, and to not perform a countermovement prior to jumping. Following familiarization, participants performed three maximal trials with 60 seconds rest between jumps. Trials were discounted and repeated if any of the following errors occurred: failure to remain still during countdown, hands were removed off hips, or a visible countermovement was observed from firstly watching the athlete and secondly analyzing the force trace. All trials and data were analyzed using a customized LabVIEW program and the variables measured included: PF_{abs}, PF_{allo}, jump height, average RFD (RFD_{avg}), relative RFD_{avg}, peak velocity (PV), peak power (PP), relative peak power (PP_{rel}), impulse, PRFD, and time to peak rate of force development (tPRFD). Acceptable reliability has previously been reported for the SJ protocol using youth athletes [30].

Countermovement jump

Countermovement jumps (CMJ) were recorded using an AMTI force plate sampling at 1000 Hz (Accupower, AMTI, Boston, MA, USA). All data were processed using a Butterworth filter. In line with previous research, participants were instructed to perform maximal effort jumps with hands remaining on hips throughout to limit the influence of the upper body on jump performance [31]. Participants were able to descend to a self-selected depth during the eccentric portion of the jump. The same verbal cues were given before each trial, "*jump as high as you can in 3, 2, 1, go".* Three maximal effort trials were recorded per participant with a minimum of 60 seconds rest between trials. During the countdown participants remained still to optimize stabilization of body weight and establish a baseline prior to the jump. All trials and data were exported from the Accupower software (Accupower 3.0, Accupower solutions, Boston, MA, USA) and analyzed using a validated automated spreadsheet [32]. The variables measured for CMJ analyses were; jump height, reactive strength index modified (RSI_{mod}), PF_{abs}, PF_{allo}, eccentric impulse (ECC_{imp}), duration of eccentric phase (ECC_{dur}), concentric impulse (CON_{imp}), duration of concentric phase (CON_{dur}), PP, PP_{rel}, eccentric power (ECC_{pow}), concentric power (CON_{pow}), and time to take off. Acceptable reliability has previously been reported for the CMJ protocol using youth athletes [33].

Statistical analyses

Descriptive statistics (means ± SD) were calculated for all performance variables for each group (*Table 1*). The Shapiro-Wilk test was used to examine normal distribution for all test variables and BSA total score was determined to be non-parametric across all cohorts. Therefore, a Kruskal-Wallis H test with Bonferroni post-hoc analysis was used to determine differences between groups and median BSA total score was subsequently reported. To ensure that ratio scaling had adequately controlled for the effect of body mass on force production, Pearson correlation coefficients (r) were calculated between PF_{rel} and body mass. Correlations between PF_{rel} and body mass was low for the SJ and CMJ tests ($r < 0.12$), suggesting that allometric ratio scaling had adequately controlled for the effect of size on force production. One-way analysis of variance (ANOVA) with Bonferroni post-hoc analysis was used to determine the differences between the three maturity groups for the IMTP, SJ, and CMJ variables. Homogeneity of variance was determined using Levene's test for equality of variances, and where violated, Welch-ANOVA with a Games-Howell post-hoc was subsequently used. Effect sizes were calculated to interpret the magnitude of between-group effects according to Cohen's *d* statistic, using the following thresholds: <0.20 (trivial), 0.20-0.59 (small), 0.60-1.19 (moderate), 1.20-1.69 (large), and >1.70 (very large) [34]. Regression slopes describing the rate of change were calculated within each maturity group for PF_{abs} and PF_{allo} from the IMTP, SJ, and CMJ test performance with advancing maturity using Microsoft Excel (v. 2016, Redmond, Washington, USA). One-way ANOVA were used to determine any significant between-group differences for the regression slopes of each test variable. With data pooled across all participants multiple stepwise linear regressions were used to determine predictor variables for both CMJ and SJ height. The Durbin-Watson statistic was used to detect autocorrelation in residuals from the regression analyses and multicollinearity was determined using variation inflation factor (VIF) and tolerance diagnostics. All statistical analyses were computed using SPSS (V.24 Chicago, IL, USA), with statistical significance for all tests set at an alpha level of $p < 0.05$.

RESULTS

Back squat assessment

Analysis revealed a small difference for median BSA total scores between the post-PHV group (3.0) and the pre-PHV group (4.5) ($p < 0.001$, $d = 0.34$). No significant differences were observed between the circa-PHV group (3.5) and either the pre- or post-PHV groups.

Isometric mid-thigh pull

Results for all IMTP variables are displayed in *Table 2*. Analysis showed that PF_{abs}, PRFD, PF50, PF90, PF150, PF200, and PF250 all significantly increased with advancing maturity ($p < 0.001$). All absolute force values during the IMTP increased between each maturity group, and differences tended to be large from both pre- to circa-PHV and circa- to post-PHV, and very large differences between pre to post-PHV ($p < 0.05$). PRFD also significantly increased with maturity but with moderate effects between consecutive groups and a large effect from pre- to post-PHV ($p < 0.05$). PF_{allo} significantly increased between each group with moderate to large effect sizes. However, non-significant, trivial differences were reported between all maturity groups for both tPF and $PRFD_{rel}$ ($p > 0.05$).

Squat jump

Results for all SJ variables are displayed in *Table 3*. Analysis revealed that PF_{abs}, jump height, RFD_{avg}, PV, PP, PP_{rel}, impulse, PRFD, and tPRFD all significantly increased with advancing maturity ($p < 0.05$). Very large increases were revealed in PF_{abs} and PP with increasing maturity status ($p < 0.05$). There were moderate differences observed for jump height between the pre- (12.81 cm) to circa-PHV (15.45 cm) groups and the circa- to post-PHV (19.10 cm) groups; however, a very large difference was observed between the pre- to post-PHV group ($p < 0.05$, $d = 1.90$). Moderate differences were also revealed between the pre- to circa-PHV groups and circa- to post-PHV groups for PF_{allo}, RFD_{avg}, PV, relative power, impulse, PRFD, and tPRFD ($p < 0.05$). However, differences when comparing the pre- to post-PHV groups often became large or very large, with the exception of relative RFD_{avg}, PRFD and tPRFD which showed a significant and moderately difference ($p < 0.05$).

Countermovement jump

Results for all CMJ variables are displayed in *Table 4*. Analysis of CMJ variables revealed that PF_{abs}, jump height, RSI_{mod}, ECC_{imp}, CON_{imp}, peak landing force, PP, PP_{allo}, ECC_{pow}, and CON_{pow} all increased with advancing maturity status ($p < 0.05$). Large to very large differences were observed in PF_{abs}, ECC_{imp}, CON_{imp}, PP, ECC_{pow}, and CON_{pow} between the pre- to circa-PHV and pre- to post-PHV groups ($p < 0.05$). Also, large and very large differences were seen for ECC_{imp}, PP, ECC_{pow}, and CON_{pow} between the circa- to post-PHV groups ($p < 0.05$). Increases for jump height were revealed moderate differences between the pre- (17.45 cm) to circa- PHV (21.31 cm) and the circa- to post-PHV (25.43 cm) groups; however, there was a very large difference between the pre- to post- PHV ($p < 0.001$, $d = 2.03$) groups. Moderate differences were also observed for RSI_{mod} for all comparisons between the pre- (0.24), circa- (0.28) and post-PHV (0.32) groups. Moderate differences for PF_{allo} and PP_{rel} were observed between consecutive maturity groups; however, comparisons between pre- to post-PHV groups revealed large and very large differences ($p < 0.05$). Between-group differences for time to take off, ECC_{dur} and CON_{dur} were either trivial to small or non-significant for.

Regression analyses

Mean rates of change (+95% CI) for stature and body mass are displayed in *Figure 1*. Analyses revealed a significant difference between regression slopes for stature ($p < 0.05$), but not for body mass ($p > 0.05$). The greatest within-group variability for both stature and body mass were observed by the circa-PHV groups.

Mean rates of change for PF_{abs} and PF_{allo} in the IMTP, SJ and CMJ within each maturity group are displayed in *Figure* 2. The circa-PHV group were consistently experiencing the greatest rate of change in both PF_{abs} and PF_{allo} in each of the IMTP, SJ and CMJ; however, given the large variability in the circa-PHV group regression slope analyses revealed no significant differences between groups for rate of change for PF_{abs} and PF_{allo} in any protocol ($p > 0.05$). Of note, the slopes for IMTP PF_{abs} ($p = 0.069$), SJ PF_{abs} ($p = 0.063$) and SJ PF_{allo} ($p = 0.080$) were approaching significance.

Across all participants, multiple stepwise linear regression models significantly predicted 45% and 48% of variance in SJ height and CMJ jump height, respectively ($p < 0.05$). Regression analyses determined that IMTP PF_{allo} was the strongest predictor of SJ and CMJ jump height, explaining 34.8% and 41.3% of the total explained variance, respectively (Table 5). Maturity offset was the next greatest predictor of jump height within both regression models. BSA total score had a negative relationship for both SJ and CMJ jump height; however, BSA total score was only included in the final linear regression model for the SJ. For all stepwise multiple regression models, there was no evidence of multicollinearity (r <0.70), along with acceptable values for tolerance (>0.1) and VIF (<10).

DISCUSSION

The main aim of the present study was to examine how movement competency, strength, and power differed between pre-, circa- and post-PHV male athletes with no prior experience of strength and conditioning. The post-PHV group displayed better overall movement competency in the BSA than the pre-PHV group, but not the circa-PHV group. IMTP data revealed PF_{abs}, and PF at all time epochs all significantly increased with advanced maturity with large to very large between group differences. Similar findings were observed in the SJ and CMJ test, where analysis of the force-time variables revealed more mature athletes were able to produce a greater amount of force (e.g. PF_{abs} and PF_{allo}). This was particularly evident for peak power in both the SJ and CMJ tests, where very large differences were displayed between consecutive maturity groups. RFD_{avg} and PRFD within the SJ also displayed very large increases with advancing maturity. Between-group differences can be partially explained by the different rates of change experienced within each group; the period of circa-PHV was associated with the largest rates of changes, although the high variability of change during this period meant that differences to other groups were not significant. Across all participants IMTP PF_{allo} was the strongest predictor of both SJ and CMJ height, suggesting the importance of absolute strength relative to allometrically scaled body weight for achieving a high jump height.

Analysis of the median BSA total scores revealed a small significant decrease in the number of technical deficiencies between the pre-PHV and post-PHV groups (4.5 to 3.0); however, there were no significant differences between consecutive maturity groups. These findings indicate that movement competency increases non-linearly across maturity groups; however, more sizeable changes may take longer to manifest following the adolescent growth spurt. This aligns with previous cognitive and motor skill development literature in youth which suggests that more meaningful movement competency improvements can be made prior to the adolescent growth spurt [3,16,35]. Cumulatively, the data indicate that small improvements in movement competency appear to occur naturally as a result of growth and maturation. Since the participants in the current study had no formal training background, conceivably further improvements in their movement competency could be made by introducing a developmentally-appropriate training programme.

Findings from the IMTP analyses revealed that advanced maturity improves not only maximal force production, but also the ability to produce force quickly. This notion is based on the large to very large effect size differences between maturity groups for PF_{abs} and PF at all time epochs (d >1.20) as well as the moderate differences observed for peak RFD (d = 0.63 to 1.16) between maturity groups. Interestingly, effect sizes were consistently greater for nearly all variables between pre- and circa-PHV groups compared to circa- to post-PHV. More mature athletes tend to have greater mass in comparison to children, which gives an advantage for absolute measures of strength; akin to those observed in the present study for PF_{abs}, PRFD, and PF at all time epochs. Previous literature comparing differences in force producing capabilities between children and adolescents noted that adolescents display a heightened neural drive, greater muscle size, and improved muscle activation patterns which aid in more notable increases in force production at this stage of development [4,19,22,36]. In the current study, differences for IMTP PF_{allo} revealed moderate effect sizes between the circa- vs. post-PHV ($d = 0.65$) groups and a slightly larger but still moderate difference between the circa- vs. pre-PHV groups ($d = 1.14$). This would indicate that the rate of adaptation for force production is slightly greater during the pre-adolescent to pubertal period of maturation. However, regression analyses for rate of change with respect to maturity offset revealed a near-significant between-group difference in the regression slopes of the IMTP PF_{abs}. Similarly, the confidence intervals for mean rate of change demonstrated larger variations within the circa-PHV group compared to the pre- and post-PHV groups. Therefore, it should be acknowledged that while the period of rapid growth within the circa-PHV group likely resulted in greater absolute force production, the level of within-group variation affected maturational between-groups values for PF_{abs}.

The overall findings from the SJ test were that PF_{abs}, PF_{allo}, jump height, average RFD, peak velocity, and PP all increased significantly with advancing maturity status. Regression analyses in all maturity groups for PF_{abs} and PF_{allo} revealed non-significant differences in slopes, however, they were approaching significance ($p = 0.063$ and $p = 0.080$, respectively). Similar to IMTP PF_{abs}, the near-significant differences in slopes suggest that increased rates of adaptation for absolute and allometrically-scaled force production are likely a result of growth and maturation during the period around PHV. However, caution is warranted due to the larger confidence intervals observed in mean scores by the circa-PHV group, which inherently leads to greater between-group comparisons. Very large between-group differences were reported for PP between all groups. Meanwhile, moderate effect size differences were evident for peak velocity and PF_{allo} which suggests that increases in SJ PP during maturation are driven by greater force production and changes in velocity. In comparison to children, adolescent athletes have physiological advantages for producing high-velocity concentric force [10,19]. A review on muscle power by Van Praagh et al. [10] suggested that adolescents increase lower body velocity through longer limb length and faster muscle contractile properties, allowing for greater angular velocity around joints and quicker force production, respectively. This likely influenced the peak power scores for the circa- and post-PHV groups but did not increase absolute force production during the SJ. In conclusion, our results indicate that changes to peak power in the SJ as a result of maturation are driven from increases in velocity and force.

Overall findings from CMJ analysis were that PF_{abs}, jump height, ECC_{imp}, CON_{imp}, PP, PP_{rel}, ECC_{pow}, and CON_{pow} all increased with advanced maturity based off the moderate to very large between-group differences. Therefore, it appears that the onset of puberty also brings about slightly greater adaptations in CMJ kinetic variables for producing force quickly. Analysis of the force-time variables within the CMJ indicate that the post-PHV group had a moderately longer duration in the eccentric phase than both the circa- and pre-PHV groups ($d = 0.46$). Despite a longer eccentric phase, there were no differences between groups for duration in the concentric phase and time to take off, which indicates that the post-PHV group utilizes a longer eccentric phase during the SSC in order to produce greater force. The longer eccentric phase duration might indicate that the more mature group were more effective at relying on cross-bridge formation as the primary stretch-shortening cycle mechanism for CMJ performance, which is indicative of slow-SSC activities [4,10,37,38]. This explanation is supported by the significantly greater RSI_{mod} observed by the post-PHV group over both the pre- and circa-PHV cohorts despite having a greater time to takeoff. Higher RSI_{mod} values typically reflect explosive jump performance and are characterized by greater absolute force, power, and velocity within the eccentric phase [39]. Therefore, the data indicate that maturity improves the eccentric phase-specific qualities relevant to CMJ performance.

Between group differences in the IMTP, SJ, and CMJ tests appear to be driven by the variance in rates of change by the circa-PHV group. The regression slopes between the maturational groups were significantly different for stature but not body mass. The largest variance for rates of change was observed in the circa-PHV cohort and were much lower in the pre- and post-PHV groups. These differences within the circa-PHV group reflects the variable timing and tempo of maturation. Similarly, the significant differences in stature likely influenced force producing capabilities during the isometric and dynamic performance tests. This aligns with previous literature which indicates that morphological increases as a result of maturation increase strength and power [4,10].

Stepwise linear regression models identified that IMTP PF_{allo} explained most of the variance in both the SJ (34.8%) and CMJ (41.3%) regression models, followed by a small predictive contribution from maturity status. This indicates that allometrically scaled force production during isometric actions appears to be an important variable of those measured for explosive vertical jump performance in young male athletes and should therefore be targeted within strength and conditioning programs for young athletes. These findings are in accordance with previous pediatric literature that has advocated the development of a foundation of strength in order to significantly increase power [40]. Both linear regression models also identified maturity status as predictors for SJ and CMJ jump height, suggesting that a more mature status will facilitate jumping higher. These findings reflect existing literature that that has shown advanced maturity being influential to both jump height and lower body power [6,11,13,14,37].

PERSPECTIVE

The overall findings indicate that natural growth and maturation induces positive adaptations to movement competency as well as isometric and dynamic strength and power. Squat movement competency improves with maturation, however, the current study did not control for behavioral factors such as physical activity levels which are also likely to enhance overall movement competency. Furthermore, it is unclear whether natural improvements to movement competency are noticeable towards the beginning or end stages of the adolescent growth spurt. Maturity resulted in significant improvements for PF_{abs} and PF_{allo} in the IMTP, SJ, and CMJ, suggesting that adaptations to force producing qualities accompany natural physical growth and development. However, it cannot be determined if greater adaptations occur during the pre- to circa-PHV period or the circa- to post-PHV period due to the large variation in rates of change from the circa-PHV group. Thus, it is difficult to identify when the greatest period of increased force production occurs. Linear regression analyses revealed that IMTP PF_{allo} positively influences jump height in both the SJ and CMJ. This finding highlights the importance of greater force production in relation to body mass for young athletes during lower body power movements. While natural growth improves force production, resistance training aimed at improving muscle strength levels can improve force producing capabilities in young athletes regardless of maturity status.

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Figure 1. Mean rate of change and 95% CI for stature and body mass.

Figure 2. Mean rate of change and 95% CI for within-group scores for PF_{abs} and PF_{allo} in the IMTP, SJ, and CMJ tests.

Table 1. Mean (± SD) values for descriptive details of each maturity groups anthropometric data.

	N	Standing height (cm)	Mass (kg)	Maturity offset (years from PHV)
Pre-PHV	130	148.02 ± 7.72	41.22 ± 7.98	-2.17 ± 0.65
Circa-PHV	33	164.12 ± 5.74*	55.48 ± 8.06*	-0.01 ± 0.36*
Post-PHV	43	175.94 ± 6.96**	70.15 ± 10.54**	1.92 ± 0.68**

* significantly greater than pre-PHV group ($p < 0.001$)

** significantly greater than circa-PHV group ($p < 0.001$)

Table 2. Group means (± SD) for IMTP kinetic force-time variables and effect-sizes (ES) with 95% confidence intervals (CI) for between-group differences.

	Pre-PHV	Circa-PHV	Post-PHV	Pre- vs. Circa- (*d*) (95% CI)	Circa- vs. Post- (*d*) (95% CI)	Pre- vs. Post- (*d*) (95% CI)
Absolute PF (N)	1216.70 ± 238.89	1766.99 ± 306.04	2244.77 ± 362.99	2.00** (1.71 – 2.59)	1.42** (0.91 – 1.88)	3.34** (3.19 – 4.20)
Allometric Scaled PF (N/kg$^{0.67}$)	102.16 ± 13.96	120.35 ± 17.59	131.98 ± 17.78	1.14** (0.83 – 1.62)	0.65* (0.20 – 1.10)	1.86** (1.58 – 2.36)
Time to PF (ms)	2820.16 ± 1137.16	2554.55 ± 948.88	2793.58 ± 1110.29	0.25 (-0.13 – 0.61)	0.23 (-0.21 – 0.67)	0.02 (-0.31 – 0.36)
Peak RFD (N·s^{-1})	4621.23 ± 1450.88	6624.94 ± 1956.78	7891.94 ± 2054.74	1.16** (0.87 – 1.67)	0.63** (0.18 – 1.07)	1.83** (1.60 – 2.39)
Relative Peak RFD (N·s^{-1}/kg)	114.53 ± 38.11	119.58 ± 39.17	114.25 ± 33.80	0.13 (-0.24 – 0.50)	0.14 (-0.29 – 0.58)	0.00 (-0.33 – 0.34)
PF 50ms (N)	391.56 ± 89.06	550.66 ± 108.98	726.58 ± 153.77	1.59** (1.28 – 2.11)	1.32** (0.80 – 1.76)	2.66** (2.58 – 3.5)
PF 90ms (N)	444.11 ± 95.15	640.45 ± 123.58	833.42 ± 155.50	1.78** (1.49 – 2.35)	1.37** (0.86 – 1.82)	3.02** (2.91 – 3.88)
PF 150ms (N)	547.81 ± 127.03	815.59 ± 151.74	1034.79 ± 192.87	1.91** (1.58 – 2.44)	1.26** (0.75 – 1.71)	2.98** (2.81 – 3.77)
PF 200ms (N)	624.27 ± 146.48	961.61 ± 209.94	1178.00 ± 215.41	1.86** (1.64 – 2.51)	1.01** (0.54 – 1.47)	3.00** (2.81 – 3.77)
PF 250ms (N)	742.95 ± 193.13	1142.23 ± 241.90	1416.22 ± 257.85	1.82** (1.52 – 2.37)	1.09** (0.61 – 1.55)	2.95** (2.69 – 3.63)

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* significant between-group differences ($p < 0.05$)

** significant between-group differences ($p < 0.001$)

Table 3. Group means (± SD) for SJ kinetic force-time variables and effect-sizes (ES) with 95% confidence intervals (CI) for between-group differences.

	Pre-PHV	Circa-PHV	Post-PHV	Pre- vs. Circa- (*d*) (95% CI)	Circa- vs. Post- (*d*) (95% CI)	Pre- vs. Post- (*d*) (95% CI)
Absolute PF (N)	842.64 ± 176.01	1184.62 ± 216.77	1530.87 ± 271.90	1.73** (1.41 – 2.26)	1.40** (0.89 – 1.86)	3.00** (2.85 – 3.81)
Allometric Scaled PF (N/kg$^{0.67}$)	71.57 ± 10.41	81.26 ± 10.31	91.04 ± 13.78	0.93** (0.54 – 1.31)	0.80** (0.33 – 1.23)	1.59** (1.32 – 2.08)
Jump height (cm)	12.81 ± 2.67	15.45 ± 3.76	19.10 ± 4.64	0.80** (0.51 – 1.28)	0.86** (0.39 – 1.30)	1.66** (1.51 – 2.28)
Average RFD (N·s^{-1})	1492.97 ± 713.15	2358.66 ± 845.68	3440.58 ± 1543.09	1.10** (0.77 – 1.55)	0.86** (0.37 – 1.28)	1.62** (1.55 – 2.33)
Relative Avg. RFD (N·kg^{-1})	35.44 ± 14.37	42.30 ± 13.66	49.56 ± 22.39	0.48** (0.10 – 0.86)	0.39 (0.07 – 0.82)	0.75* (0.49 – 1.18)
Peak Velocity (m·s^{-1})	1.97 ± 0.16	2.09 ± 0.22	2.30 ± 0.23	0.62** (0.31 – 1.07)	0.93** (0.46 – 1.38)	1.66** (1.43 – 2.20)
Peak Power (W)	1340.14 ± 274.51	1961.58 ± 371.74	2896.05 ± 567.01	1.90** (1.64 – 2.52)	1.94** (1.35 – 2.40)	3.49** (3.59 – 4.68)
Relative Power (W·kg^{-1})	32.71 ± 3.94	35.74 ± 6.26	41.41 ± 6.56	0.57* (0.29 – 1.05)	0.88** (0.42 – 1.33)	1.60** (1.43 – 2.20)
Impulse (Ns)	1.69 ± 0.23	1.89 ± 0.22	2.10 ± 0.25	0.88** (0.49 – 1.26)	0.89** (0.42 – 1.33)	1.70** (1.35 – 2.11)
Peak RFD (N·s^{-1})	4066.91 ± 1965.92	5641.72 ± 2147.30	7170.99 ± 3370.60	0.76** (0.40 – 1.16)	0.54* (0.08 – 0.96)	1.12** (0.92 – 1.64)
Relative Peak RFD (BW(N)·s^{-1})	10.18 ± 4.79	10.36 ± 3.80	10.52 ± 5.09	0.04 (-0.33 – 0.41)	0.03 (-0.40 – 0.47)	0.06 (- 0.26 – 0.40)
Time to Peak RFD (ms)	211.69 ± 121.08	153.12 ± 74.52	119.13 ± 60.85	0.58** (0.14 – 0.89)	0.49** (0.06 – 0.95)	0.96* (0.50 – 1.19)

* significant between-group differences ($p < 0.05$)

** significant between-group differences ($p < 0.001$)

Table 4. Group means (± SD) for CMJ kinetic force-time variables and effect-sizes (ES) with 95% confidence intervals (CI) for between-group differences.

	Pre-PHV	Circa-PHV	Post-PHV	Pre- vs. Circa- (*d*) (95% CI)	Circa- vs. Post- (*d*) (95% CI)	Pre- vs. Post- (*d*) (95% CI)
Absolute PF (N)	473.20 ± 122.27	723.58 ± 172.51	930.81 ± 212.01	1.67** (1.43 – 2.28)	1.07** (0.58 – 1.51)	3.01** (2.56 – 3.47)
Allometric Scaled PF ($N/kg^{0.67}$)	40.08 ± 8.93	49.05 ± 9.35	54.77 ± 12.01	0.98** (0.60 – 1.38)	0.53* (0.07 – 0.96)	1.38** (1.12 – 1.85)
Jump Height (cm)	17.45 ± 3.39	21.31 ± 5.23	25.43 ± 5.10	0.87** (0.61 – 1.39)	0.79** (0.34 – 1.25)	1.84** (1.64 – 2.42)
RSI modified (JH/time to take off)	24.40 ± 6.74	28.90 ± 7.66	32.92 ± 7.61	0.62** (0.27 – 1.02)	0.52* (0.08 – 0.97)	1.18** (0.86 – 1.57)
Eccentric Impulse (Ns)	36.01 ± 8.49	55.28 ± 9.76	73.85 ± 16.70	2.10** (1.75 – 2.63)	1.35** (0.82 – 1.78)	2.85** (2.87 – 3.83)
Concentric Impulse (Ns)	76.10 ± 15.67	114.43 ± 20.13	154.49 ± 26.20	2.12** (1.84 – 2.73)	1.71** (1.16 – 2.17)	3.63** (3.56 – 4.63)
Peak Power (W)	1414.04 ± 303.29	2208.77 ± 451.33	3152.05 ± 650.70	2.06** (1.88 – 2.78)	1.76** (1.12 – 2.13)	3.62** (3.55 – 4.63)
Relative Peak Power (W/kg)	34.94 ± 4.77	39.38 ± 5.83	45.03 ± 6.45	0.83** (0.50 – 1.27)	0.91** (0.44 – 1.36)	1.77** (1.52 – 2.30)
Eccentric Power (W)	-168.79 ± 41.52	-249.30 ± 56.83	-345.99 ± 91.80	1.61** (1.36 – 2.19)	1.26** (0.74 – 1.69)	2.48** (2.53 – 3.44)
Concentric Power (W)	759.25 ± 173.09	1193.44 ± 238.79	1675.19 ± 359.28	2.08** (1.84 – 2.74)	1.57** (1.03 – 2.02)	3.24** (3.33 – 4.37)

* significant between-group differences ($p < 0.05$)

** significant between-group differences ($p < 0.001$)

Table 5. Stepwise multiple linear regression equations explaining the variables that significantly ($p < 0.05$) contributed to SJ and CMJ jump height for all maturity groups.

Dependent variable	Independent variables	Regression equation	Adjusted R^2 value
SJ jump height	Constant	10.08	
	IMTP PF_{allo}	0.05	0.348
	Maturity Offset	1.48	0.417
	IMTP $PRFD_{rel}$	0.04	0.430
	IMTP PRFD	0.0006	0.445
	BSA Total Score	-0.24	0.452
CMJ jump height	Constant	9.56	
	IMTP PF_{allo}	0.10	0.415
	Maturity Offset	1.87	0.458
	IMTP $PRFD_{rel}$	0.06	0.468

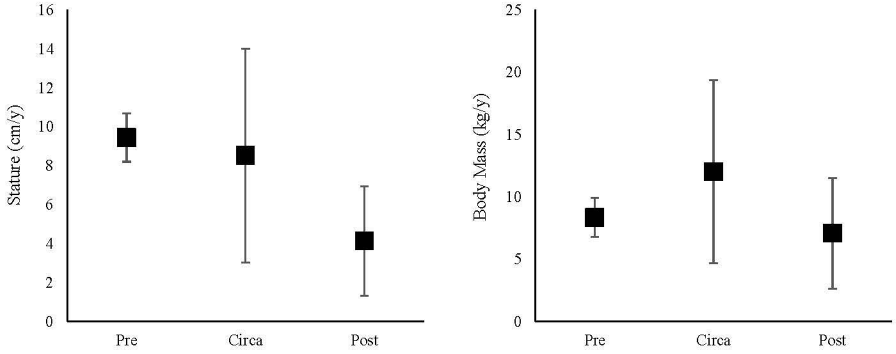

Figure 1. Mean rate of change and 95% CI for stature and body mass.

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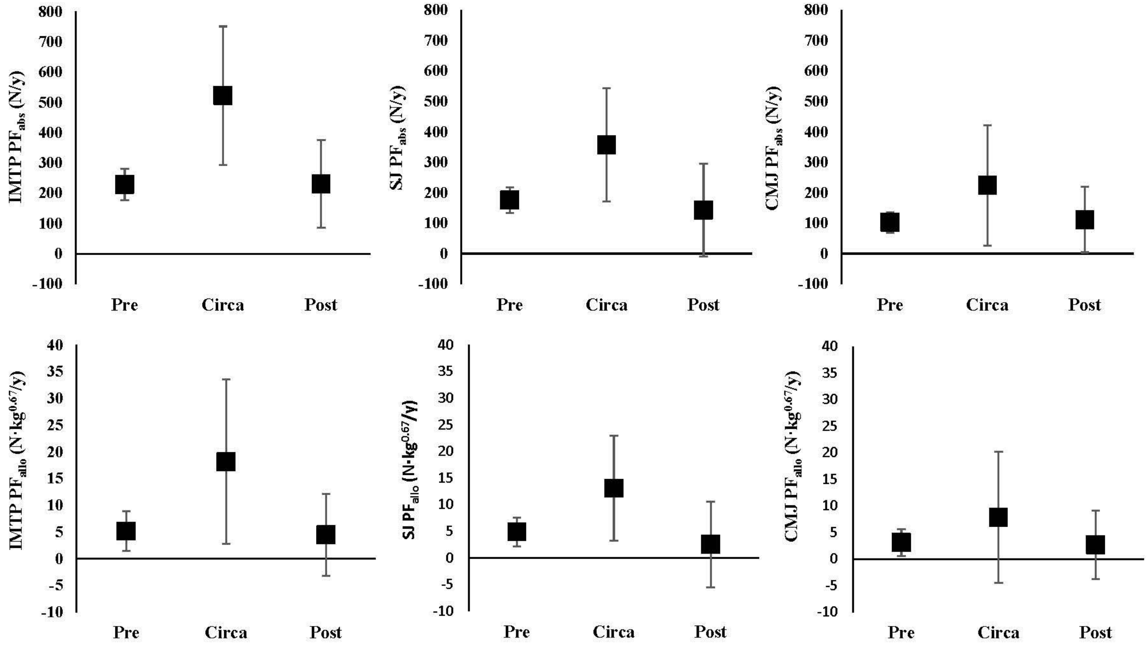

Figure 2. Mean rate of change and 95% CI for within-maturity group scores for PF$_{abs}$ and PF$_{allo}$ in the IMTP, SJ, and CMJ tests.

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