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MUSCLE ARCHITECTURE AND MATURATION INFLUENCES SPRINT AND JUMP ABILITY IN YOUNG BOYS: A MULTI-STUDY APPROACH

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Abstract

This series of experiments examined the influence of medial gastrocnemius (GM) and vastus lateralis (VL) muscle architecture (muscle thickness, pennation angle, and fascicle length) on sprint and jump performance in pre-, circa- and post-peak height velocity (PHV) boys. In *experiment 1*, one-way ANOVA's and Cohen's d effect-sizes demonstrated that most muscle architecture measures were significantly greater in post- compared to pre-PHV boys ($d = 0.77 – 1.41$; $p < 0.05$). For the majority of sprint and jump variables, there were small to moderate differences between pre- to circa-, and circa- to post-PHV groups ($d = 0.58 – 0.93$; $p < 0.05$), and moderate to large differences between pre- and post-PHV groups ($d = 1.01 – 1.47$; $p < 0.05$). Pearson's correlation analyses in *experiment 2* determined that muscle architecture had small to moderate correlations with sprint and jump performance ($r = 0.228 – 0.707$, $p < 0.05$), with strongest associations within the post-PHV cohort. Chi squared analyses in *experiment 3* identified that, over 18-months, more POST-POST responders than expected made positive changes in GM and VL muscle thickness. Significantly more PRE-POST subjects than expected displayed changes in maximal sprint speed, while significantly more POST-POST individuals than

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expected showed positive changes in jump height. Muscle architecture appears to be larger in more mature boys compared to their less mature peers, and likely underlies their greater performance in sprinting and jumping tasks. Boys experiencing, or having experienced, PHV make the largest increases in muscle architecture, and sprinting and jumping performance when tracked over 18-months.

Keywords

Muscle Thickness; Fascicle Length; Longitudinal; Physical Performance; Talent ID; Youth

INTRODUCTION

Muscle architecture is a primary determinant of muscle function, with the architectural arrangement of fibres within the muscle having implications on the fascicle's force-velocity and force-length characteristics (22, 51). Longer fascicles provide an improved ability to produce force at higher velocities and over larger length ranges (4), whereas greater muscle thicknesses and pennation angles generally increase force generating capabilities (49). Muscle architecture characteristics develop throughout childhood and adolescence, resulting in increases in muscle thickness, fascicle length, and pennation angle (18, 36, 42). Children generally have smaller muscle thickness than both adults (20, 37) and older adolescents (19), while adolescents have significantly longer muscle fascicles than children, but do not differ from adults (18). Pennation angle of the knee extensor muscles appears to remain consistent from childhood through to adulthood (18, 36), whereas the pennation angle of the gastrocnemius medialis has been reported to increase from birth before stabilizing after the adolescent growth spurt (14). Recently, research has identified the differences in muscle architecture between pre-, circa-, and post-PHV boys, highlighting how more mature boys have greater thickness, pennation angle and fascicle lengths of gastrocnemius medialis (GM) and vastus lateralis (VL) compared with less mature boys (42). Differences of ~20–30% in muscle thickness, and ~10–20% in pennation angle and fascicle were reported between the post- and pre-PHV groups (42). However, this existing literature is cross-sectional in nature and therefore, the impact of growth and maturation on longitudinal changes in muscle architecture remains unknown.

Jumping and sprinting are common tasks in both active play and youth sports (23, 39) that utilise the stretch-shortening cycle (SSC). The SSC is a naturally occurring muscle action for most forms of human locomotion (15) that develops throughout childhood and adolescence, enabling children to jump higher (24, 40) and sprint faster (29, 40) as they mature. Previous research into developmental trends of vertical jump ability in children have shown improvement rates of 7% in jump height per year between U12 and U16 soccer players (52), and CMJ height increases of approximately 2 cm annually between U13 to U15 youth rugby league players (48). An adolescent performance spurt in vertical jump height seems to begin about 1.5 years prior to PHV (~ 12.5 y) with peaks occurring approximately at the time of PHV to one year after PHV (~14–15 y) (3, 40, 50). From a sprint speed point of view, maximal sprint speed may not change during the pre-PHV stage, but that significant increases in speed are detected between circa- and post-PHV groups (29). These cross-sectional data were verified in a longitudinal study of school aged youth, where boys that experienced PHV (pre-to-post-PHV change in the 21-month study) made significantly greater increases in speed (10.4 vs. 5.6%) compared to the group that stayed at pre-PHV (Meyers *et al.*, 2016). Cumulatively, these previous studies highlight that jumping and sprinting performance improves with maturation in youth, however, the role of muscle architecture on functional performance of power tasks such as sprinting and jumping activities is currently unclear. In adult populations muscle architecture of both the vastus lateralis and lateral gastrocnemius can positively influence both sprint (17, 21) and jump (11, 44) performance. However, attempting to translate adult-based literature to paediatric populations with dynamically changing morphology and hormones is extremely challenging owing to the role that growth and maturation have on physical performance at various stages of development.

In youth populations, lean leg volume can explain a significant portion of the variance ($R^2 = 0.33$) in power output during jumping in boys, measured as the average power output during 15 s of continuous jumping (47). However, the influence of independent muscle architecture characteristics on jump performance were not delineated within the study, as total muscle volume of the lower leg was the sole variable reported. Alternative research indicates that greater vastus lateralis (VL) and lateral gastrocnemius (LG) muscle thickness and VL pennation angle can explain some of the variance in peak force during the countermovement jump (CMJ: $R^2 = 0.45$, 0.44 and 0.29, respectively) and squat jump (SJ: $R^2 = 0.53$, 0.50 and 0.37, respectively) (45). However, these results should be interpreted with caution as this study pooled both sexes during a stage of development where potential maturational differences between sexes are prominent (27).

Cumulatively, these previous findings demonstrate the potential increases in muscle architecture, sprint speed and jumping performance in youth, however there remains a dearth of evidence examining the role of muscle architecture on the development of sprint and jump ability throughout childhood. Therefore, the aims of the series of studies were *firstly*, to examine differences in muscle architecture, and force-velocity-power (FVP) variables from sprinting, and countermovement jump force-time variables in pre-, circa- and post-peak height velocity (PHV) boys. *Secondly*, to determine the relationships between muscle architecture variables and key sprint and jump performance variables in boys of varying maturity status. *Thirdly,* to identify individual longitudinal adaptations in muscle architecture characteristics and associated changes in sprint and jump performance over an 18-month period. In light of these aims, the following hypotheses were proposed:

i. Study 1: Muscle architecture will be larger in the post-PHV group, compared with less mature peers. Additionally, more mature boys will have a better performance in terms of FVP and force-time variables form the sprint and CMJ.

ii. Study 2: Muscle thickness and pennation angle of the GM and VL will have some association with jump performance, while fascicle length will be associated with sprint performance.

iii. Study 3: All muscle architecture measures will increase over the 18-month period, with the greatest number of responders being from the group that are experiencing their growth spurt. Sprinting and jumping performance will improve in all groups, with the greatest number of responders coming from the PRE-POST group.

METHODS

Experimental Approach to the Problem

The first study divided the subjects into maturity sub-groups based on their age from PHV. A one-way analysis of variance (ANOVA) and Cohen's *d* effect sizes were then used to determine between group differences in muscle architecture, sprinting, and jumping ability. In the second study, Pearson correlation coefficients were used to determine the relationships between muscle architecture and sprinting and jumping ability within the maturity sub-groups. For the third study, subjects were tracked over 18 months and divided into three groups based on age from PHV at the initial testing session and 18 months later. Frequency counts were used to determine the number of individuals who made changes greater than the smallest worthwhile change, moderate worthwhile change, and large worthwhile change from each group. Chi-squared (χ^2) analyses was then used to investigate frequencies that would be considered larger in magnitude than might be expected by chance.

Subjects

The same population of male secondary school children in the United Kingdom were used across all elements of the study. Initially, one hundred and twenty participants completed the muscle architecture assessment and sprint trials; of these, eighty-six also completed the jump trials; finally, thirty-eight of these subjects were tracked longitudinally for 18-months. All participants were free from injury and were involved in sport and physical education-based activity programmes. The boys played a range of team sports, predominantly rugby and soccer, for both school and local clubs. Parental consent and participant assent were collected for all elements of the study, in addition to a standardised health questionnaire. Ethical approval was granted by the University Research Ethics Committee for all elements of the study. Standing height (cm), seated height (cm), and body mass (kg) were used to estimate biological maturity as years from PHV (33).

For the cross-sectional assessments, participants with a maturity offset of −1 to −0.5 years, and +0.5 to +1 years were removed from the study due to the error in the prediction equation of approximately 6 months for boys (16), resulting in three distinct maturity groups: pre-PHV group (maturity offset of < −1), circa-PHV (maturity offset between −0.5 – 0.5), and post-PHV group (maturity offset of >1). For the cross-sectional analyses, a post hoc power analysis was conducted (GPower, v3.1.9.4), which revealed the statistical power for this study was 0.35 – 0.47 for detecting the smallest effect size, whereas the power exceeded 0.99 and 1.00 for the detection of a moderate and large effect size, respectively. Descriptive statistics for each maturity group in the first two elements of the study are shown in Table 1.

For the longitudinal analyses, post hoc power analysis was again conducted (GPower, v3.1.9.4), which identified the statistical power for this study was 0.33 for detecting the smallest effect size, whereas the power exceeded 0.97 and 1.00 for the detection of a moderate and large effect size, respectively. Participants were classified as pre-, or post-PHV (maturity offset: < 0 years and > 0 years, respectively) at each of the two testing periods (T1 and T2). Those participants classified as pre-PHV at both T1 and T2 were termed "PRE – PRE" (n = 9), those who were pre-PHV at T1 but post-PHV at T2 were termed "PRE – POST" (n = 16), and those who were post-PHV at T1 and post-PHV at T2 were termed "POST – POST" group (n = 13). Descriptive statistics for each maturity group for the longitudinal element of the study are shown in Table 2.

Procedure

Muscle architecture assessment—Muscle structure of the GM and VL were measured with B-Mode ultrasonography (Vivid E9, GE Healthcare, Chalfont St Giles, UK) with a 45-mm linear array probe. Water soluble gel was applied to the ultrasound probe for acoustic coupling, to enhance the contrast of the images. To measure the GM, participants laid prone on a massage couch with legs fully extended, and ankle positioned at approximately 90° relative to the shank, unsupported and unloaded (11, 42). For the imaging of the VL, participants lay supine with the knee fully extended (anatomical zero) (11, 42). This scanning set-up has been shown to have moderate to excellent reliability (ICC = 0.59 – 0.97; CV = 0.6 – 11.1%) in young boys (42). For both muscles, the ultrasound probe was placed perpendicular to the skin, and the scanning surface was orientated until it was positioned parallel to the muscle to collect sagittal plane images of each subject's self-reported dominant leg. A constant, minimal pressure was applied throughout scanning to avoid depressing the dermal layer surface and influencing muscle thickness. For the VL muscle, the image was taken at 50% of the distance between the greater trochanter and the lateral epicondyle of the femur (44) and the GM image was taken at 30% of the distance from the popliteal crease to the centre of the lateral malleolus (19). Subsequent analysis of images was carried out using open-source image analysis software (Image J, National Institute of Health, Bethesda, MD, USA). Muscle thickness was measured as the perpendicular distance from the superficial aponeuroses to the deep aponeuroses; the thickness of the proximal, distal and middle of the muscle belly was assessed in the image, and the average of these sites used for further analysis. Physiological muscle thickness was calculated by the following equation: $(\text{muscle thickness}^2 + [\tan \times \text{pennation angle} \times \text{muscle thickness}]^2)^{0.5}$ (8). Pennation angle (Θ_p) was defined as the angle between the muscle fascicles and the deep aponeuroses, as the entire fascicle was not visible in the ultrasound image, it was calculated from the equation: $\text{fascicle length} = \text{muscle thickness} (\sin \Theta_p)^{-1}$ (8). Each ultrasound image was assessed on three occasions, with the average value for each variable used for analysis.

Sprint Assessment—Following the muscle scans, participants completed a standardized 10-minute dynamic warm-up inclusive of three minutes of submaximal multidirectional running and seven minutes of light dynamic mobilization and activation exercises targeting the main muscle groups of the lower extremities. Once completed, participants were allowed as many practice attempts of the test protocols (sprints and CMJ) as was required for the lead researcher to be satisfied that subjects demonstrated appropriate technique. After the familiarisation period, participants performed three trials of a maximal sprint over 30 m in an indoor sports hall. Timing gates (Smart Speed, Fusion Sport, Australia) were placed at 0 m, 5 m, 10 m, 20 m, and 30 m. Participants were instructed to begin their sprint in a split stance on a line 50 cm from the starting line and asked to sprint maximally through the timing gates. A minimum of four minutes passive rest was given between trials to ensure sufficient recovery (29). Due to the fact that the start line for the subjects was before the initial timing gate, a correction factor (mean = 0.29 s) was calculated from a sub-sample of 20 age matched young boys and added to the raw data to ensure that the time measurement of the sprints started as soon as any propulsive action was produced (43). The correction factors was calculated as the time taken between the initial positive movement and reaching the first timing gate, using a radar gun (LKG LMC-J-0310-Sport, Locke Kempf GmbH & Co., Walldorf, Germany) sampling at 99 Hz and placed five meters behind the start line (frontal plane), set at a height of 1 m corresponding with the subject's centre of mass (COM) (43). The 5, 10, 20 and 30 m split times, as well as subjects' height (m), body mass (kg) and ambient variables were then used to calculate FVP variables for each trial using a validated theoretical model in a freely available Microsoft Excel worksheet (Microsoft Excel for Mac 2016, Redmont WA, USA) (43). Theoretical maximal horizontal force (F_0), theoretical maximal velocity (V_0), maximal power output (P_{max}), mechanical effectiveness of ground force application (ratio of force (RF), and the decrease in the ratio of force over acceleration (D_{RF}), were all calculated indirectly from the sprint times (43).

Jump assessment—Participants completed three trials of a CMJ, interspersed with approximately 1-minute of rest. Participants lowered themselves from an initial standing position to a self-selected squat depth, performing the eccentric and concentric phases of the jump as quickly as possible to maximise jump height (24). Any trial that was inadvertently performed with the inclusion of an arm swing or tucking of the legs during flight was omitted, and in such cases an additional trial was performed following a 1-minute rest period. All trials were recorded at 1000 Hz using an AMTI force platform (AMTI, Boston, MA). Participants were instructed to stand still for the initial 1 s of the data-collection period (34) to allow for the subsequent determination of body weight. The raw vertical force–time data for each trial were exported and analysed using a customised Microsoft Excel spreadsheet (10); the force-time variables calculated included acceleration (m/s^2), velocity (m/s), displacement (m), and power (W). From these variables, other variables were calculated including; jump height (m), modified reactive strength index (RSI_{mod}), peak force (N), relative peak force (N/kg), eccentric impulse (N/s), concentric impulse (N/s), peak power (W), relative peak power (W/kg), concentric average power (W), and eccentric average power (W).

Statistical Analyses

Between Group Differences: Descriptive data (mean ± *SD*) were determined for the pre-, circa-and post-PHV maturity groups. Homogeneity of variance was assessed via Levene's statistic and where violated; Welch's adjustment was used to correct the F-ratio. A one-way analysis of variance (ANOVA) was conducted to identify maturity group differences in muscle architecture, and sprinting and jumping variables. Post-hoc analysis was used to identify significant between-group differences using either Bonferroni or Games-Howell post-hoc analyses, where equal variances were or were not assumed, respectively. Cohen's *d* effect sizes were calculated to establish the magnitude of any between-group differences using the following classifications: trivial < 0.19; small 0.2 – 0.59; 0.6 – 1.19 moderate; 1.2 – 1.9 large; 2.0 – 3.9 very large; > 4.0 extremely large (13).

Relationship between muscle architecture and sprint and jump performance: Relationships between muscle architecture, and each key FVP and force-time variable were assessed via Pearson's correlation coefficients, and interpreted as: < 0.2 no relationship; 0.2 – 0. 45 weak; 0.45 – 0.7 moderate; > 0.7 strong based on previous recommendations (38).

Longitudinal analysis: To facilitate the calculation of individual changes in muscle architecture, sprint performance and jump ability were calculated across the 18-month period. The smallest worthwhile change (SWC), defined as 0.2 of the between-subject standard deviation for the total sample was also calculated (41). Subsequent thresholds of 0.6 and 1.2 of the between-subject standard deviation were also calculated to reflect moderate (MWC) and large worthwhile changes (LWC), respectively. Frequency counts were used to determine the number of individuals who made changes greater than the SWC, MWC, and LWC over the course of the 18-month period to identify individuals who made small, moderate or large "positive changes". Chi-squared (χ^2) analyses were used to investigate frequency counts, with adjusted standardized residual values being interpreted using the ± 1.96 criteria, whereby values greater than 1.96 would be considered larger in magnitude than what might be expected by chance, and smaller than 1.96 considered less than might be expected by chance (26, 46). Statistical significance for all tests was set at alpha level $p < 0.05$ and all statistical procedures were conducted using SPSS v.23 for Macintosh.

RESULTS

Cross-Sectional Analysis

Maturity group differences in muscle architecture—Muscle architecture variables for all groups are displayed in table 3. For all thickness measures of both GM and VL there were significant between group differences with moderate effects from pre- to circa- ($d = 0.97 – 1.04$ (CI = 0.50 – 1.50); $p = <0.001 – 0.003$) and circa- to post-PHV ($d = 0.64 – 0.77$ (CI = 0.13 – 1.27); $p = <0.001 – 0.003$) groups, and large effects between pre to post-PHV groups ($d = 1.26 – 1.41$ (CI = 0.79 – 1.88); $p < 0.05$). For GM pennation angle, the post-PHV group had a significantly greater pennation angle than the pre- and circa-PHV groups ($d = 1.04$ and 0.69 (CI = 0.19 – 1.48), respectively; $p = <0.001$ and 0.006, respectively); however, there were no significant differences between the groups for VL pennation angle ($p = 0.135 – 1.000$). The post-PHV groups had significantly greater VL fascicle length than the pre group ($d = 0.77$(CI = 0.32 – 1.20); $p < 0.001$), but there were no other differences between groups ($p = 0.151$ and 0.386), and there was no significant difference in GM fascicle length between any groups ($p = 0.196 – 1.000$).

Maturity group differences in sprint and jump performance—FVP and force-time variables of each group are displayed in figure 1 and figure 2, respectively. There were small to large significant differences across consecutive maturity groups for relative P_{max}, RF_{max} and maximal sprint speed ($d = 0.58 – 1.43$ (CI = 0.18 – 1.91); $p = <0.001 – 0.027$). There was also a small significant difference in D_{RF} between the pre- post-PHV groups ($d = 0.22$ (CI = −0.40 – 0.44); $p = 0.018$). There were moderate, significant differences between the post-PHV group, and both the pre- and circa-PHV groups for both jump height and relative peak power ($d = 0.62 – 1.10$ (CI = 0.11 – 1.56); $p = <0.001 – 0.030$). In terms of eccentric average power, there were moderate to large, differences between all three maturity groups ($d = 0.92 – 1.47$ (CI = 0.40 – 1.93); $p < 0.001$). However, there were no significant differences between any maturity groups for relative peak force.

Relationships between muscle architecture, and force-velocity-power and force-time variables—Results of the correlation analyses are presented in table 4. Maximal sprint speed had a weak correlation with both VL muscle thickness and fascicle length in the pre-PHV group ($r = 0.232$ and 0.330, respectively; $p = 0.044$ and 0.007, respectively). Additionally, D_{RF} had a weak correlation with both GM and VL muscle thickness and fascicle length’s ($r = 0.228 – 0.272$; $p = 0.022 – 0.047$), while RF_{max} had a weak correlation with VL pennation angle ($r = −0.230$; $p = 0.046$). There was a weak correlation between GM pennation angle and maximal sprint speed in the circa-PHV group ($r = −0.349$; $p = 0.029$). Finally, in the post-PHV group, maximal sprint speed had a moderate correlation with VL fascicle length ($r = 0.528$; $p = 0.001$), and weak correlations with VL pennation angle and GM muscle thickness ($r = − 0.482$ and 0.296, respectively; $p = 0.002$ and 0.042, respectively).

From the CMJ analyses, there were no significant correlations between muscle architecture and jump height, relative peak power, or relative peak force for either the pre- or circa-PHV groups.

However, in the pre-PHV, all thickness measures of both GM and VL were negatively correlated with eccentric average power ($r = −0.405 – −0.707$; $p = <0.001 – 0.015$), in addition to VL pennation angle ($r = −0.412$; $p = 0.013$). For the circa-PHV cohort, there were weak to moderate relationships between eccentric average power and both VL thickness measures, and pennation angle ($r = −0.358$ and −0.478, respectively; $p = 0.042$ and $p = 0.009$, respectively). In the post-PHV group, there were weak to moderate correlations between GM physiological thickness, VL muscle thickness, and VL fascicle length, and jump height and relative peak power ($r = 0.243 – 0.679$; $p =< 0.001 – 0.041$). All muscle architecture measures had small to moderate correlations with eccentric average power in the post-PHV cohort ($r = −0.438 – −0.565$; $p=< 0.001 – 0.005$), excluding GM pennation angle and fascicle length and VL pennation angle.

Longitudinal Analysis

Muscle architecture changes—The number of individuals showing positive changes in each of the muscle architecture characteristics across the 18-month period are presented in figure 3 and 4. For changes above the MWC in GM and VL muscle thickness, there were significantly less PRE-PRE positive responders than expected by chance, and more POST-POST positive responders than expected by chance. Additionally, for changes above the LWC, there were significantly more POST-POST positive responders than expected by chance. Similarly, for GM and VL physiological thickness, there were less PRE-PRE positive responders than expected by chance for changes above MWC. For the number of individuals with changes above the LWC there were significantly less than expected by chance from PRE-PRE, and more than expected by chance from POST-POST. In terms of GM pennation angle, there were significantly less individuals showing positive changes above the SWC than expected by chance from PRE-POST. Finally, for all other muscle architecture variables (VL pennation angle, GM and VL fascicle length) there were no significant differences in the number of individuals showing positive changes compared to the expected.

Sprint and jump performance changes—The number of individuals showing positive changes in sprint FVP variables and force-time characteristics from the CMJ across the 18-month period are presented in table 5. From the sprint analyses, significantly more individuals than expected displayed changes in relative P_{max} above the LWC from PRE-POST, and significantly less than expected from PRE-PRE. For RF_{max}, significantly more individuals showed positive changes than expected above the LWC from PRE-POST. In terms of maximal sprint speed, there were significantly more individuals than expected showing positive changes above the MWC from PRE-POST. However, there were no differences in the number of individuals displaying positive changes from any groups for D_{RF}.

From the jump analyses, significantly more individuals than expected in POST-POST showed changes above the LWC in jump height. Significantly fewer individuals than expected made changes above the SWC in the PRE-PRE for relative peak power. Additionally, there were no differences to the expected number for the number of individuals making positive changes in relative peak force or eccentric average power.

DISCUSSION

This series of studies identified that most muscle architecture variables were larger in post-PHV boys compared with pre-PHV boys. Similarly, data indicated that post-PHV boys outperformed their less mature peers in most sprinting and jumping variables. Fascicle length in the VL seems to be an important architecture variable for sprint performance, as it was significantly correlated with maximal sprint speed and D_{RF} in the pre-PHV group, as well as with maximal sprint speed, RF_{max} and relative P_{max} in the post-PHV cohort. Muscle thickness was identified as a more important muscle architecture variables for jump performance, with significant correlations with eccentric average power in the pre- and circa-PHV groups, while VL muscle thickness and fascicle length were significantly correlated with all jump measures in the post-PHV group. The individual, longitudinal analysis indicated that PRE-POST and POST-POST experienced the largest changes in muscle architecture and generally showed larger changes in sprint and jump performance than boys who remained pre-PHV during the 18-month period. Notably, 80% of individuals that made changes above the LWC in maximal sprint speed, and 50% that made changes above the LWC in any force-time characteristic, also made LWC in VL muscle and physiological thickness, highlighting the importance of VL muscle thickness for driving potential improvements in sprint and jump performance. Therefore, the first hypothesis can be accepted that muscle architecture, and sprinting and jumping ability are greater in post-PHV boys. The second hypothesis can be accepted where muscle thickness was associated with jump performance, and fascicle length associated with sprint performance. Finally, the third hypothesis can partially be accepted, where muscle architecture increased, and sprinting and jumping performance improved across 18-months, but the greatest number of responders were from the POST-POST group for muscle architecture and jump performance, rather than the PRE-POST group. However, there were more responders from PRE_POST for improvements in sprint speed.

Cross-sectional findings

Between group differences—The current study found that muscle architecture variables, excluding GM fascicle length and VL pennation angle, were larger in the post-PHV cohort compared with the pre-PHV group. Additionally, both GM and VL muscle and physiological thickness was significantly larger in the post- than the circa- group, and in the circa-, compared to the pre-PHV group. These results are in accordance with a recent study, where it was found that a post-PHV cohort had greater muscle thickness, pennation angle, and fascicle length of the GM and VL, excluding GM fascicle length, compared with the pre-PHV cohort (42). Adaptations to the size of the muscle, and architectural arrangement, throughout maturation may occur due to increases in body mass, intensifying the mechanical load on the skeletal system during everyday tasks (4). Additionally, changes in height will also enhance muscle growth, as the load or stretch applied to muscles during bone growth may act as a stimulus for increases in muscle size (53).

The increase in maximal sprint speed from pre-, to circa-, and into post-PHV is similar to earlier findings (29, 40), and while the increases in sprint speed across maturation may not be novel, the changes in FVP variables with maturation may be of greater interest. The present study found that relative P_{max}, RF_{max}, and maximal sprint speed significantly increased from pre-, to circa-, to post-PHV, while D_{RF} was significantly greater in the post-PHV group compared to the pre-PHV group. Recently, a number of researchers have demonstrated that a forward orientation of force (RF_{max}) has been suggested as an important predictor of sprint speed in elite adult sprinters (35). This current finding, where increases in RF_{max} were observed across pre-, circa-, and post-PHV groups, may suggest that increases in speed with maturation are attributed to a greater technical ability, that develops naturally in boys, allowing more force to be orientated in the forward direction.

In terms of force-time variables during the CMJ, the post-PHV group had significantly greater performance than the pre-PHV cohort. Considering that the pre- and circa-PHV groups had similar jump heights, but the post-PHV group had greater jump height than the circa-PHV group, this suggests that jump height tends to increase following the adolescent growth spurt. The notion that increases in jump height mainly occur following PHV are consistent with the findings in previous research (40). Additionally, there were no differences in relative peak force between any of the maturity groups, but differences in relative peak power were identified between pre- to post-PHV and then circa- to post-PHV groups, suggesting that there is more of an influence of body mass on increases in absolute force production compared to power production as children mature. Considering that maximal power is the product of force and velocity, the development of velocity during maturation may be driven by additional factors other than just muscle mass. For example, VL fascicle length has been shown to increase throughout maturation (42) and would permit a greater ability to produce force at higher contraction velocities and over larger length ranges, as more sarcomeres in series results in greater cumulative length change of a fascicle within a given time (9).

Relationship between muscle architecture and physical performance— Correlation analyses identified that maximal sprint speed demonstrated associations with VL muscle thickness and fascicle length in the pre-PHV cohort. Similar findings were also identified in the post-PHV group, where maximal sprint speed was associated with GM muscle thickness and VL fascicle length. Sprinters in general demonstrate greater vastus medialis thickness than untrained subjects (17), however previous research indicates that it was fascicle length rather than muscle size that was able to differentiate between subgroups of highly trained sprinters (sub 10-second versus sub 11-second 100 m times) (21). This may explain the findings in the current study, where fascicle length was the best predictor of sprint performance in the pre- and post-PHV groups. The importance of fascicle length during sprinting may be explained by the influence that an increased number of sarcomeres in series have upon the maximum shortening velocity of muscle (22). Considering that ground contact times during sprinting range between 0.137 – 0.147 s for boys (32), there is a need for rapid force production for successful sprint performance. Longer fascicles may have a positive influence on rate of force development (RFD), which may ultimately enhance sprinting performance by reducing ground contact times, leading to an improved mechanical efficiency by a greater reutilisation of elastic energy (12). Notably, VL fascicle length demonstrated a stronger association with maximal sprint speed in the post-PHV group compared to the pre-PHV group, highlighting that in the less mature cohort sprint speed may be underpinned by neural factors rather than the structural factors measured during this study. Boys who are pre-PHV are more stride frequency reliant, relying more heavily on neural contributions to facilitate a higher cadence (30). Conversely the data might suggest that post-PHV boys may be more stride length dependent relying more on muscle architecture, including fascicle length, to produce higher RFD (30).

There were no relationships between relative P_{max} and muscle architecture in the pre- or circa-PHV groups. Conversely, in the post-PHV group, there were significant, moderate associations between relative P_{max} and VL fascicle length and pennation angle. These results may be due to the immature muscle architecture in the pre- and circa-PHV cohorts; while these are undergoing significant changes throughout maturation, they may have less of an impact on relative power production during a sprint. The noted relationship between RF_{max} and VL fascicle length in the post-PHV group suggests that in the more mature group, boys with longer fascicles were better at directing force in a more forward orientated position. Furthermore, both pre- and post-PHV groups showed significant small relationships with GM muscle thickness and D_{RF}, indicating that the GM may have a role in reducing the inevitable decrease in the ratio of force directed horizontally. However, it needs to be highlighted that the associations between these variables were weak in nature.

From the CMJ analyses, eccentric average power, was the primary force-time variable that was associated with muscle architecture variable in the pre- and circa-PHV groups. However, in the post-PHV cohort, as well as the significant relationships between muscle architecture measures and eccentric average power, there were significant relationships between GM physiological thickness, VL muscle thickness and VL fascicle length, and jump height and relative peak power. These findings may suggest the differing role that the VL and GM muscles have during jumping tasks in adolescents. Considering that physiological thickness accounts for both pennation angle and thickness, the role of the GM may be more responsible for force output, while the association between longer fascicles in the VL and CMJ performance would support the notion that longer fascicles will increase contraction speed (6). It could therefore be assumed that the muscles take on more specialised roles for jumping performance. Specifically, as children mature the GM may adopt a role of force production, whereas the VL muscle may be required to produce higher levels of velocity.

Longitudinal findings

Longitudinal 18-month tracking of subjects showed significantly more individuals than expected made changes above the MWC and the LWC for the POST-POST, and significantly less than expected from the PRE-PRE for muscle and physiological thickness of the GM and VL. These findings suggest that individuals may make the greatest changes in thickness variables during and after the adolescent growth spurt. Previous research has identified increases in arm and calf girths with age, with larger changes around 13–14 years in boys (27), coinciding with the average age of PHV. At this point, there is approximately a 10-fold increase in testosterone production in boys (50), which may explain the rapid increases in muscle mass during and after PHV, as seen in the current study (27, 50).

The lower number of individuals than expected making positive changes in GM pennation angle from PRE-POST may be due to the greater variability in maturity changes within this group. While all children in this group experienced PHV, they appeared to have progressed at different tempos of growth during this period. Notably, ten of the PRE-POST group underwent positive changes in GM pennation angle, while six actually experienced negative changes, thus highlighting the large inter-individual variation in GM pennation angle during this stage of development. This variability in muscle architecture changes as children experience PHV highlights the difficulty in making future predictions on development (i.e. talent ID), and from a practical perspective, this underlines the need for training to be made specific to the child to optimise the interaction between training, and growth and maturation.

With respect to FVP variables from the sprints, there were more individuals than expected displaying positive changes from PRE-POST for RF_{max} and maximal sprint speed. Additionally, there were more individuals than expected with positive changes from PRE-POST, but less than expected from PRE-PRE for relative $P_{max,}$. Cumulatively, these results suggest that PHV is a key time in speed development, where individuals who have, or are experiencing PHV make greater changes in force-velocity-power variables. Similar results have been reported in previous literature, where peak improvements in 30 m sprint time coincided with PHV (40). This developmental trend was recently verified in a longitudinal study, where boys that experienced PHV made significantly greater increases in speed compared to the group that stayed at pre-PHV (31).

For all participants that made changes above the LWC in maximal sprint speed, 80% made LWC in VL muscle and physiological thickness. Similarly, for all participants that made changes above the LWC in RF_{max}, D_{RF}, and P_{max}, at least 50% of them also made LWC in VL muscle and physiological thickness. These findings indicate the role of muscle thickness adaptations in inducing positive changes in sprint performance, and previous research has reported relative peak force had very large and large relationships with sprint speed in young boys, respectively (28). A greater muscle thickness in the VL muscle may result in more force being produced during the sprint, due to the relationship between muscle size and force output in children (49).

In terms of the force-time characteristics derived from the CMJ, data suggests that the larger changes in jump performance may occur in individuals who are post-PHV, as there were significantly more individuals than expected from the POST-POST cohort that increased jump height. These results are in accordance with previous longitudinal data, as studies have suggested an adolescent performance spurt in vertical jump height to begin about 1.5 years prior to PHV with peaks occurring approximately at the time of PHV to one year after PHV (27, 40, 50). Similar trends have been found in youth football, where the cumulative increase in CMJ performance from U12-U16 was very strongly related to age ($R^2 = 0.98$) (52). Combined, these results demonstrate that lower body power improves with age due to the adaptations related to growth and maturation.

As with sprint speed, the importance of muscle thickness for driving potential improvements in jump performance was evident. For all participants who made changes above the LWC in any force-time characteristic, 50% of them also made LWC changes in VL muscle and physiological thickness. The importance of muscle thickness on jump performance has been demonstrated in a previous study with adolescent surfers (45), with thickness of the VL and LG muscle shown to predict 45% and 44% of the variance in peak force during the CMJ (45). Intuitively, this increased muscle thickness would result in a greater potential for force production during the CMJ (49), due to an increase in the number of contractile elements. Cumulatively, these results suggest that increases in VL muscle thickness appears to positively influence jump performance in boys.

Interestingly, the cross-sectional research highlighted the importance of VL fascicle length for successful performance in sprinting and jumping tasks in youth, evidenced by the significant relationships between VL fascicle length and the FVP variables from the sprint and the force-time variables from the CMJ. However, the longitudinal analyses demonstrated that increases in VL muscle thickness may be the driver for improvements in sprint and jump performance. These findings may suggest that fascicle length is more of an innate quality, and that having longer fascicles in the VL is preferable, but these change less with growth than muscle thickness. Fascicle length determines contraction velocity, and contraction velocity influences ground contact times (GCT) during sprinting. Previous studies have demonstrated that GCT is a strong predictor of sprint performance (32) but GCT does not improve with advancing maturity (29). Therefore, it seems that VL fascicle length can predict some of the variance in sprint speed in pre- and post-PHV boys, but does not increase extensively throughout maturation. The findings from the current longitudinal study highlight that VL muscle thickness has more scope to change, and can therefore have a larger contribution to ongoing improvements in propulsive force, increasing performance in jumping and sprinting tasks. Therefore, from a practical point of view, athletes who have longer fascicles of the VL are at an advantage in terms of producing quicker movement speed, but this may not be a quality that develops with maturity. However, muscle thickness can increase naturally with maturation and can lead to some improvements in sprinting and jumping ability.

Limitations

The series of studies have made a novel contribution to the developmental literature surrounding paediatric muscle architecture. However, it is important to consider certain limitations within the study, such as the small dimensions of the linear probe being used making it necessary to estimate fascicle length from measures of muscle thickness and pennation angle using a previously published equation (8). While this model assumes that fascicles are straight and does not account for fascicule curvature, this equation has been used in previous studies and has been shown to result in an error of only approximately 3% for relaxed muscles with short fascicles (5). While physical activity within physical education classes was controlled via the national curriculum for all participants, the habitual and extra-curricular activities of each participant were not recorded. Furthermore, while the current body of works has enhanced the knowledge of the impact of growth and maturation on muscle architecture development in boys, the developmental trend in females remains unclear. Considering that the maturational process differs between sexes (i.e. girls have less of an increase in hormones around PHV and are susceptible to natural increases in fat mass (27)), there may be a different response to muscle architecture throughout maturation in this cohort. Disparities in architecture between the sexes may result in different muscle architecture characteristics influencing performance, which would then require an alternative training prescription to males. However, notwithstanding these limitations, these studies have made an original contribution to the paediatric literature by highlighting how natural growth and development can influence muscle architecture and performance.

PRACTICAL APPLICATIONS

Cumulatively, the findings from these series of studies indicate that muscle architecture (thickness and fascicle length), sprint performance and jump performance is greater in post-PHV boys, compared to circa- and pre-PHV cohorts. In addition, muscle architecture has the greatest influence on sprinting and jumping ability in post-PHV boys. Furthermore, the adolescent growth spurt appears to be a key timepoint for positive changes in muscle architecture and physical performance in young boys, with more individuals than expected making positive improvements from the groups that were experiencing or had experienced their growth spurt. The longitudinal analyses highlight that increases in VL muscle thickness are likely the driver for improvements in sprint and jump performance. These findings may suggest that fascicle length is more of an innate quality, and that having longer fascicles in the VL is preferable but these change less with growth than muscle thickness. Therefore, practitioners may want to focus their training efforts on developing increases in muscle thickness of the quadricep muscles, as well as including modes of training that elicit increases in fascicle length. Due to the role that heavy strength training may have on enhancing muscle thickness (1, 7) and the increases in fascicle length reported following high-velocity movement training in adults (8), a periodized strength training programme that includes both heavy loads and high-speed movements may be the most appropriate to develop muscle architecture variables that optimise jump performance in young boys. While the influence of specific training methods on the development of unique muscle architecture changes is still unknown in paediatric populations, previous studies have reported the benefit of combined strength and power training methods on measures of speed and explosive power in young boys (2, 25, 41). Additionally, from a talent identification point of view, sports that require high levels of sprint speed may want to include muscle architecture assessment, and determination of fascicle length as an assessment strategy.

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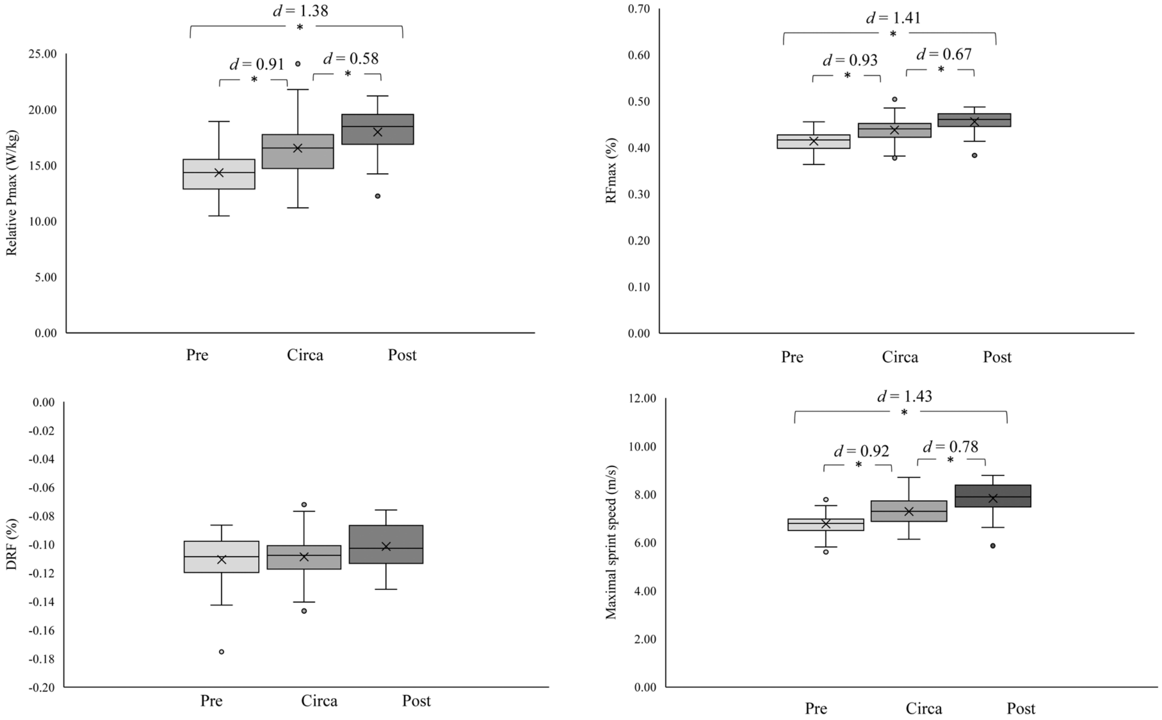


Figure 1:

Differences between maturity groups for force-velocity-power variables from the sprints

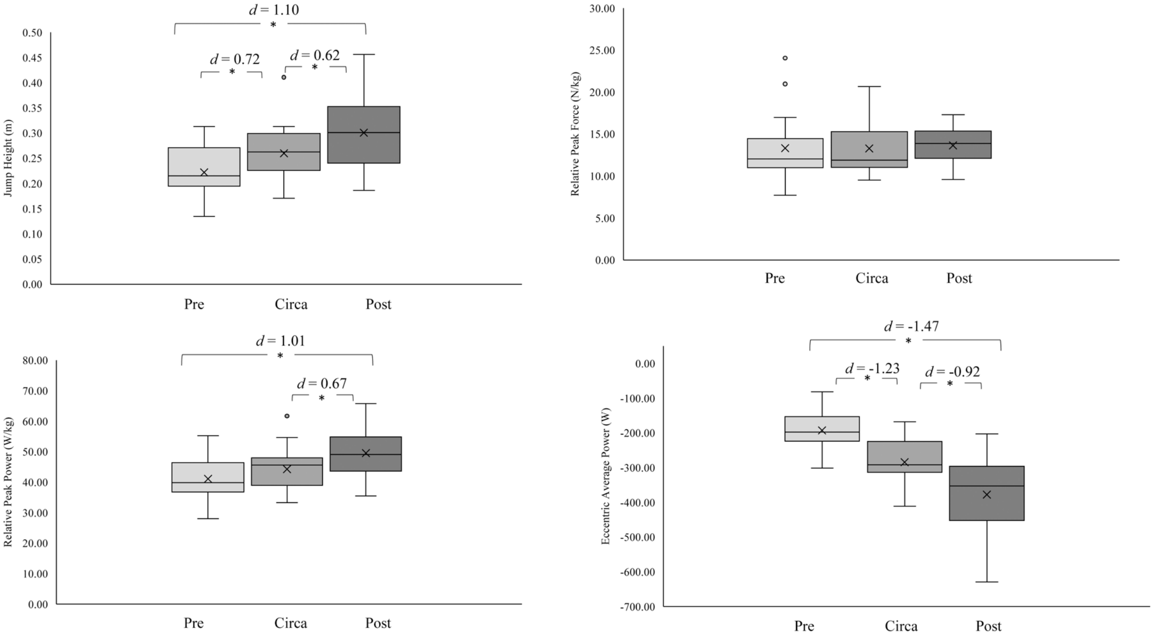
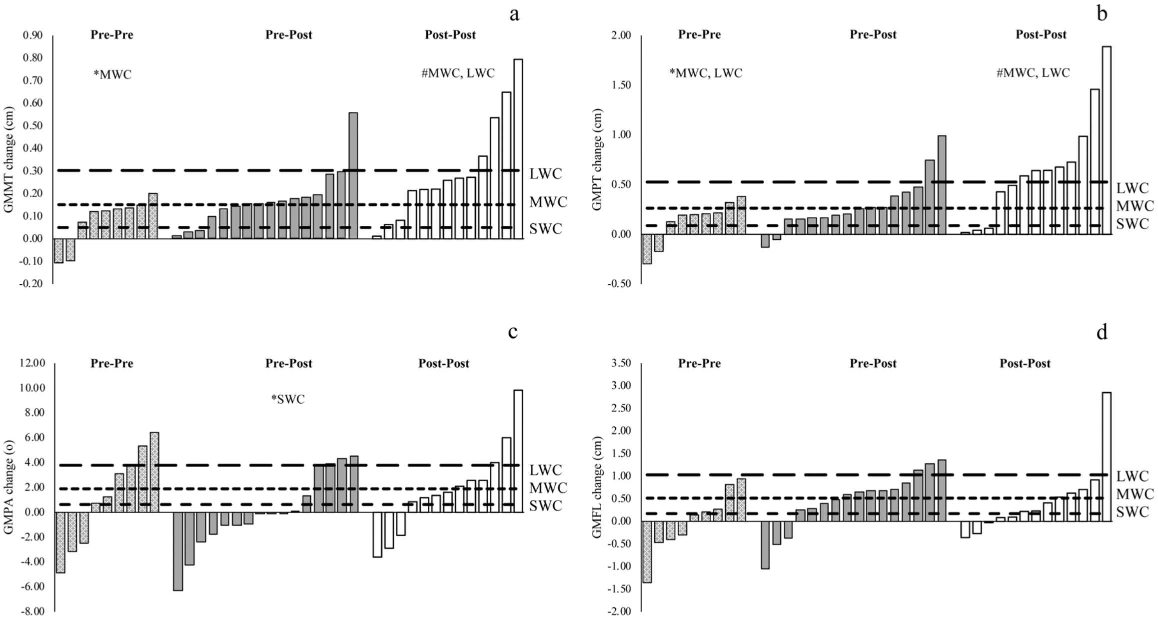


Figure 2:

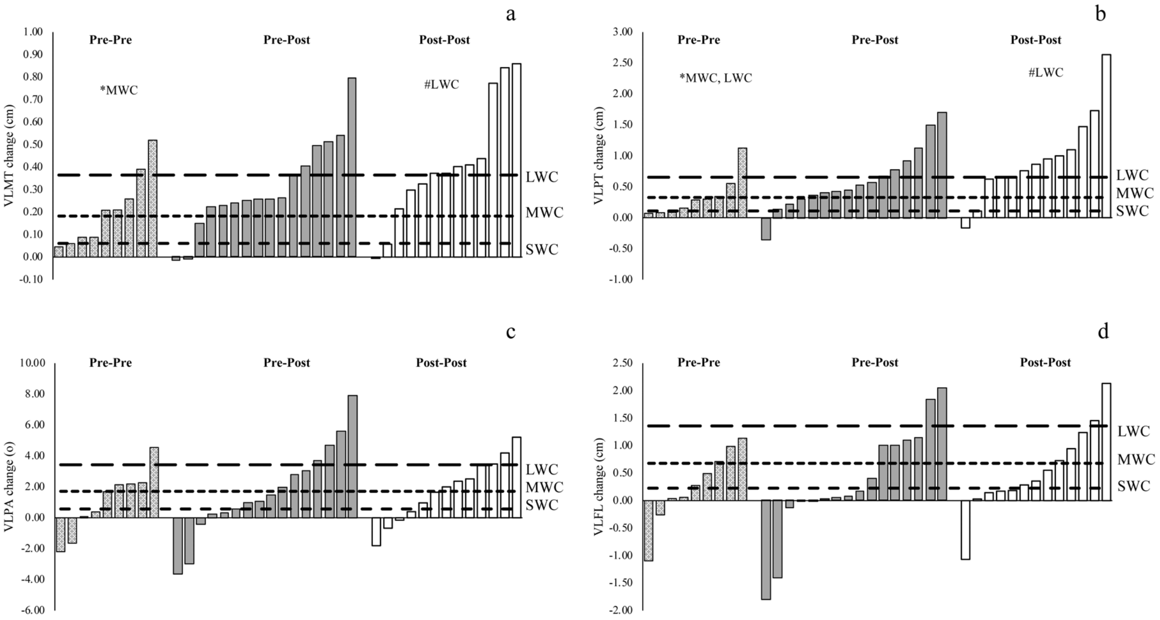
Differences between maturity groups for force-time variables from the countermovement jumps



*Less than expected by chance
more than expected by chance

Figure 3:

Frequency count of individuals with changes above smallest worthwhile change (SWC), moderate worthwhile change (MWC), and largest worthwhile change (LWC) for medial gastrocnemius muscle architecture variables



*Less than expected by chance
more than expected by chance

Figure 4:

Frequency count of individuals with changes above smallest worthwhile change (SWC), moderate worthwhile change (MWC), and largest worthwhile change (LWC) for vastus lateralis muscle architecture variables

Table 1:

Descriptive statistics for subjects in the first two elements of the study (Mean ± SD)

		Pre-PHV	Circa-PHV	Post-PHV
Number (n)	Sprints	55	30	35
	Jumps	29	24	33
Age (yrs)	Sprints	12.47 ± 0.55	14.06 ± 0.70	16.11 ± 1.25
	Jumps	12.39 ± 0.51	14.00 ± 0.74	16.11 ± 1.25
Standing Height (cm)	Sprints	152.6 ± 6.4*#	167.7 ± 5.5*	177.6 ± 6.5
	Jumps	152.01 ± 5.87	167.44 ± 5.13*	177.76 ± 5.94*#
Leg Length (cm)	Sprints	75.9 ± 4.8*#	82.4 ± 4.5*	84.1 ± 4.6
	Jumps	74.85 ± 5.07	81.81 ± 4.29*	83.68 ± 4.43*#
Body Mass (kg)	Sprints	42.2 ± 5.9*#	56.5 ± 9.0*	73.6 ± 12.7
	Jumps	41.72 ± 5.60	56.40 ± 9.36*	73.39 ± 12.51*#
Maturity Offset (yrs)	Sprints	−1.73 ± 0.47	0.10 ± 0.26	2.39 ± 1.00
	Jumps	−1.72 ± 0.47	0.11 ± 0.25	2.39 1.02

*significantly different to Post-PHV group ($p < 0.05$)

#significantly different to Circa-PHV group ($p < 0.05$)

Table 2:

Descriptive statistics for anthropometric variables, and percentage change across the 18-month period (Mean ± SD)

	PRE – PRE (n = 9)			**PRE – POST (n = 16)**			**POST – POST (n = 13)**		
	T1	**T2**	**%**	**T1**	**T2**	**%**	**T1**	**T2**	**%**
Age (yrs)	12.4 ± 0.2	13.9 ± 0.2		13.0 ± 0.6	14.5 ± 0.6		14.3 ± 0.4	15.7 ± 0.4	
Standing Height (cm)	152.8 ± 5.2	160.7 ± 6.8	5.1 ± 2.1[a]	161.5 ± 5.0	170.0 ± 4.0	5.9 ± 1.9[a]	173.4 ± 8.5	176.5 ± 8.2	2.3 ± 1.8
Leg Length (cm)	74.8 ± 3.9	79.2 ± 4.6	5.9 ± 2.9[a]	78.4 ± 4.5	83.3 ± 3.6	6.7 ± 2.8[a]	83.7 ± 6.4	85.2 ± 6.1	2.8 ± 2.5
Body Mass (kg)	40.7 ± 4.6	46.5 ± 5.4	14.2 ± 6.4	53.7 ± 8.4	60.5 ± 8.3	14.7 ± 9.4	72.2 ± 9.5	76.0 ± 9.7	8.6 ± 7.9
Maturity Offset (yrs)	−1.7 ± 0.3	−0.6 ± 0.4		−0.6 ± 0.4	0.7 ± 0.5		0.8 ± 0.6	1.9 ± 0.5	

[*] significantly greater than the pre- test ($p < 0.05$)

[a] significantly greater change than the POST-POST ($p < 0.05$)

Table 3:

Differences between maturity groups for muscle architecture variables (Mean ± SD)

Muscle architecture variable	Pre-PHV	Circa-PHV	Post-PHV
GM Muscle Thickness (cm)	1.47 ± 0.17[*#]	1.70 ± 0.24[*]	1.92 ± 0.30
GM Physiological Thickness (cm)	1.67 ± 0.26[*#]	2.05 ± 0.44[*]	2.56 ± 0.74
GM Pennation Angle (degrees)	19.30 ± 3.12[*]	20.65 ± 3.67[*]	23.39 ± 3.77
GM Fascicle Length (cm)	4.56 ± 0.81	4.93 ± 0.94	4.91 ± 0.93
VL Muscle Thickness (cm)	1.83 ± 0.23[*#]	2.13 ± 0.28[*]	2.41 ± 0.43
VL Physiological Thickness (cm)	2.11 ± 0.39[*#]	2.63 ± 0.59[*]	3.17 ± 0.95
VL Pennation Angle (degrees)	16.59 ± 3.23	17.54 ± 4.09	18.17 ± 3.73
VL Fascicle Length (cm)	6.60 ± 1.31[*]	7.35 ± 1.61	7.99 ± 2.15

[*] significantly lower than post-PHV ($p < 0.05$)

[#] significantly lower than circa-PHV ($p < 0.05$)

Table 4:

Correlations between muscle architectural variables and key performance variables during the sprint and CMJ for the maturity groups

Performance Variable		Group	GMMT	GMPT	GMPA	GMFL	VLMT	VLPT	VLPA	VLFL
Sprint FVP	Relative Pmax (W/kg)	Pre	−0.135	−0.165	0.052	−0.103	−0.035	−0.08	−0.183	0.117
		Circa	−0.027	0.152	−0.115	0.067	0.163	0.082	−0.162	0.218
		Post	0.104	0.065	−0.173	0.218	0.182	−0.276	−0.461*	0.465*
	RFmax (%)	Pre	−0.031	−0.171	0.025	−0.009	0.031	−0.162	−0.230*	0.204
		Circa	−0.019	0.24	−0.163	0.116	0.178	0.101	−0.194	0.26
		Post	0.171	0.064	−0.146	0.252	0.198	−0.241	−0.478*	0.492*
	DRF (%)	Pre	0.272*	−0.037	−0.09	0.270*	0.258*	−0.188	−0.058	0.228*
		Circa	0.032	0.203	−0.302	0.299	0.073	0.057	0.095	−0.088
		Post	0.315*	0.027	0.264	0.063	0.123	0.02	−0.228	0.278
	Max Speed (m/s)	Pre	0.147	−0.126	−0.03	0.16	0.232*	−0.178	−0.212	0.330*
		Circa	−0.003	0.29	−0.349*	0.294	0.16	0.067	−0.071	0.092
		Post	0.296*	0.062	0.122	0.155	0.218	−0.129	−0.482*	0.528*
CMJ FT	Jump Height (m)	Pre	0.178	0.162	0.115	0.033	0.002	0.04	0.02	0.117
		Circa	0.032	−0.044	−0.216	0.196	0.254	0.093	−0.078	0.21
		Post	0.235	0.348*	0.265	−0.011	0.422*	0.149	−0.453*	0.679*
	EAP (W)	Pre	−0.405*	−0.423*	−0.161	−0.154	−0.670*	−0.707*	−0.412*	−0.057
		Circa	−0.135	−0.084	0.086	−0.189	−0.478*	−0.358*	0.005	−0.360*
		Post	−0.450*	−0.544*	−0.219	−0.216	−0.565*	−0.544*	−0.04	−0.438*
	Relative Peak Power (W/kg)	Pre	0.261	0.233	0.049	0.151	0.024	0.024	0.081	−0.094
		Circa	0.114	0.036	−0.173	0.209	0.215	0.059	−0.071	0.151
		Post	0.243	0.308*	0.257	0.006	0.320*	0.058	−0.465*	0.591*
	Relative Peak Force (N/kg)	Pre	0.138	0.07	−0.171	0.252	−0.11	−0.134	0.04	−0.126
		Circa	0.123	−0.073	−0.073	0.113	0.065	−0.058	−0.119	0.088
		Post	0.111	0.162	0.171	−0.023	0.096	−0.015	−0.261	0.246

[*] significant correlation between variables ($p < 0.05$)

Table 5:

Frequency count of positive responders for FVP variables from the sprint and force-time variables from the CMJ

		SWC ($SD^{*}0.2$)			MWC ($SD^{*}0.6$)			LWC ($SD^{*}1.2$)		
		Pre-Pre (n = 9)	Pre-Post (n = 16)	Post-Post (n = 13)	Pre-Pre (n = 9)	Pre-Post (n = 16)	Post-Post (n = 13)	Pre-Pre (n = 9)	Pre-Post (n = 16)	Post-Post (n = 13)
Sprint	Relative P_{max}	8	15	11	5	13	9	1^{*}	$10^{\#}$	6
	RF_{max}	8	15	10	5	12	9	2	$8^{\#}$	3
	D_{RF}	2	6	4	1	4	2	1	0	1
	Max Speed	4	12	8	3	$10^{\#}$	4	0	3	2
Jump	Jump Height	6	12	12	5	10	10	2	5	$8^{\#}$
	EAP	7	11	10	5	9	6	2	3	5^
	Rel Peak Force	4	10	8	3	6	4	1	1	2
	Rel Peak Power	4^{*}	13	11	3	10	9	1	4	4

[*] less than expected ($p < 0.05$)

[#] more than expected ($p < 0.05$)