TITLE: INFLUENCE OF MUSCLE ARCHITECTURE ON MAXIMAL REBOUNDING IN YOUNG BOYS

BRIEF RUNNING HEAD: MUSCLE ARCHITECTURE AND REBOUNDING IN BOYS

AUTHORS:
John M. Radnor [1]
Jon L. Oliver [1, 2]
Charlie M. Waugh [4]
Gregory D. Myer [5, 6, 7, 8, 9, 10]
Rhodri S. Lloyd [1, 2, 3]

AFFILIATIONS:
1. Youth Physical Development Centre, School of Sport and Health Sciences, Cardiff Metropolitan University, United Kingdom
2. Sport Performance Research Institute New Zealand, AUT University, New Zealand
3. Centre for Sport Science and Human Performance, Waikato Institute of Technology, Hamilton, New Zealand
4. Department of Physical Therapy, University of British Columbia, Vancouver BC, Canada
5. Division of Sports Medicine, Cincinnati Children’s Hospital Medical Center, Cincinnati, Ohio, USA
6. Department of Pediatrics and Orthopaedic Surgery, College of Medicine, University of Cincinnati, Cincinnati, OH, USA
7. Emory Sport Performance and Research Center, Flowery Branch, GA, USA
8. Emory Sports Medicine Center, Atlanta, GA, USA
9. Department of Orthopaedics, Emory University School of Medicine, Atlanta, GA, USA
10. The Micheli Centre for Sports Injury Prevention, Boston, MA, USA

CORRESPONDENCE
Name: John M. Radnor
Address: Youth Physical Development Centre, School of Sport and Health Sciences, Cardiff Metropolitan University, Cyncoed Campus, Cyncoed Road, Cardiff, CF23 6XD
Telephone: 02920 205592
Email: jradnor@cardiffmet.ac.uk

ABSTRACT

The aims of the current study were to i) investigate differences in maximal rebound jump kinetics in boys at different stages of maturity, and ii) determine the relationship of muscle architecture characteristics to maximal rebound jump kinetics. One hundred twenty-seven male, secondary school children were categorised into maturity groups (pre-, circa- and post-PHV) based on their maturity offset value. Muscle architecture of the gastrocnemius medialis (GM) and vastus lateralis (VL) was evaluated at rest using B-Mode ultrasonography. Participants then performed maximal rebound jumps quantified on a force platform. There were moderate to large, differences across all maturity groups for peak ground reaction force (GRF), impulse measures and average power variables ($d = 0.73 – 2.67$; $p < 0.05$). GM and VL muscle thickness explained between 38.5-55.8% of the variance in peak force, impulse and power variables, however muscle architecture was less important determinant of contact time, jump height, reactive strength index (RSI), rate of force development (RFD), eccentric velocity, concentric velocity, and allometrically scaled measures (3.3 – 17.2%). The current results indicate that the majority of kinetics employed during maximal vertical rebounding are greater in more mature boys. Furthermore, maturational increases in GM muscle architecture appears important for maximal vertical jumping, and are specifically associated with increased force, power and impulse measures. Practically, these findings may underline benefits in targeting resistance training activities that are focused to increase lower limb muscle mass to positively influence maximal rebounding kinetics in young boys.

KEY WORDS: Fascicle Length, Muscle Thickness, Hopping, Jumping, Youth, Maturation

INTRODUCTION

The stretch-shortening cycle (SSC) is a naturally occurring muscle action that involves an initial lengthening (eccentric action) prior to a subsequent shortening (concentric action) of the same muscle (29). The SSC action is fundamental to most tasks, including jumping and sprinting, which are common in both active play and competitive sports (31). However, SSC function in youth has often been assessed using basic countermovement vertical jump tests which, due to extended ground contact times and lack of pre-activation and rapid transition from stretch to shortening, reflect slow-SSC function (21). The maximal vertical rebound test may provide a more useful model of functional-SSC behaviour, due to the rapid and brief eccentric actions and shorter ground contact times (21). The maximal rebound test consists of self-regulated repeated jumps in place, and is cued to ensure athletes jump for maximal height with minimal ground contact time. Compared to sub-maximal hopping, where subjects rebound in time to a metronome, maximal hopping results in a lower rebounding frequency, increased jump heights and ground contact times (due to greater angular displacements at the hips, knees and ankles), and reduced stiffness (22).

Innate SSC development throughout childhood and adolescence enables children to jump higher (33) and sprint faster (24) as they mature. Research examining the effects of maturation on maximal vertical rebounding is sparse; although recent research has suggested that reactive strength index (RSI; calculated as jump height divided by ground contact time) in both a 20 cm and 40 cm drop jump is better in more mature boys (6). However, using standardised drop jump heights fails to account for individual differences in reactive strength capabilities and any 'optimal' stimulus is likely to be transient in nature (1). Therefore, the use of maximal rebounding has become more popular (18). For example, through the use of the maximal 5-rebound vertical jump test, there is an increase in reactive strength index (RSI) performance in boys between the ages of 10 and 16 years (20), with the largest increase in performance occurring between the ages of 10 and 11 years (20). However, the use of contact mats for the analysis of SSC function limited this study to only reporting performance-oriented variables (i.e. jump height, contact time, and RSI); therefore, the influence of underlying kinetics on SSC function during maximal rebounding in youth remains is not fully delineated (20).

Improvements in maximal rebound jump performance with maturation may be due to increases in neural factors, demonstrated by evidence that 15-year-old boys produce significantly greater levels of pre load muscle activation compared to 9- and 12-year olds during maximal rebound jumping (22). Increased preactivation increases joint stiffness, and reduces ground contact times, resulting in a more efficient SSC action during a rebound jump (34). Beyond neural influences, structural factors may also underlie improvements in maximal vertical rebounding performance throughout maturation, as, children have shown a smaller tendon excursion, and greater muscle length changes compared to adults during rebound tasks at different frequencies (39). The inability to create the required muscle stiffness to resist deformation reduces tendon excursion, resulting in less storage and return of elastic energy and therefore less efficient force generation during sport movements (39). Children may have less efficient muscle activation strategies and a reduced ability to create muscle stiffness during rebound tasks, resulting in inferior performance (39). Considering the arrangement of the fascicle within a muscle fibre and its influence on a global muscle’s function (5), the specific muscular architecture control the ability to perform maximal vertical rebounding in youth, but to date this notion remains unsubstantiated.

Muscle architecture is typically characterised by parameters such as fascicle length, pennation angle and cross-sectional area (2, 19), and these muscle architecture characteristics develop naturally throughout childhood and adolescence (17, 32). Muscle architecture has direct association with countermovement jump (CMJ) performance in youth (35, 37) and thickness of the gastrocnemius medialis and vastus lateralis muscles are associated with a greater performance in the eccentric phase of the CMJ in all stages of maturation in young boys (33). Specifically, VL muscle thickness and fascicle length are associated with greater jump height and relative peak power output in post-PHV boys (33) and increases in VL muscle thickness during natural growth and maturation is postulated as a key driver for increases in jump performance in male youth (33). While muscle thickness of the ankle and knee extensors are clearly important determinants for CMJ performance in young boys, it is yet to be determined how muscle architecture influences the kinetics of maximal jump rebounding.

Therefore, the aims of this study were to i) investigate differences in maximal rebounding kinetics in boys at different stages of maturity, and ii) determine the strength of relationships between maximal rebounding kinetics and muscle architecture characteristics. In light of previous studies, the hypotheses for the study were: i) post-PHV subjects would have greater force, impulse and power values across all kinetic variables during maximal rebound jumping, compared with their less mature counterparts and ii) muscle thickness will be the specific muscle architecture characteristic that determines maximal rebounding kinetic performance.

METHOD

Experimental Approach to the Problem

This study used a cross-sectional design to assess the differences in maximal rebounding performance between pre-, circa-, and post-PHV boys. Additionally, muscle architecture characteristics (muscle thickness, pennation angle and fascicle length) of both the GM and VL were derived using ultrasonography. A one-way ANOVA was used to identify differences in force-time characteristics between pre-, circa-, and post-PHV cohorts during maximal rebounding, while Pearson correlation coefficients and multiple stepwise regression analyses were used to examine the relationships between muscle architecture characteristics and force-time characteristics of maximal rebounding.

Subjects

One hundred and twenty-seven male secondary school children in the United Kingdom volunteered to participate in the study. A priori power analysis was conducted (GPower, v3.1.9.4) using previously published means and standard deviations of RSI across pre-, circa, and post-PHV (23) indicating the required sample size for the current study would need to be 90 subjects (30 per maturation group) to achieve a statistical power of 0.8 for detecting a moderate effect size (0.6* standard deviation). All participants were free from injury for the 6 months prior to the study and were involved in regular sport and physical education-based activity programmes, but were not receiving formal strength and conditioning support. Written parental consent and participant assent were obtained from all participants prior to the study commencing. Ethical approval for the study was granted by the Universities Research Ethics Committee (15/4/01R) in accordance with the declaration of Helsinki.

Procedures

All participants attended their usual physical education lessons as part of their school curriculum, where all testing took place. Participants were asked to refrain from strenuous exercise at least 48 hours prior to testing.

Maturity status: Biological maturity was assessed non-invasively by incorporating measures of body mass (kg), standing height (cm) and seated height (cm), measured using electronic scales (SECA 770, Vogel and Halke, Germany) and a stadiometer (SECA 321, Vogel and Halke, Germany) respectively, into a sex-specific regression equation to predict age from peak height velocity (PHV) (26). For the between-maturity group analysis, due to the error in the maturity offset prediction equation, participants with a maturity offset between -1.0 to -0.5 years, or +0.5 to +1.0 years were eliminated from the study (n = 28) to ensure three distinct maturity groups (pre-, circa- and post-PHV). The pre-PHV group included all participants with a maturity offset of <-1.0, -0.5 – 0.5 were classified as circa-PHV, and >+1.0 classified as post-PHV (see *table 1*). For the regression analyses all 127 subjects were included (mean ± SD - age: 13.73 ± 1.42 years; height: 163.61 ± 11.13 cm; body mass: 55.28 ± 15.05 kg; maturity offset: -0.22 ± 1.50 years).

***** Table 1 inserted near here *****

Muscle Architecture: 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. To measure the GM, participants laid prone on a massage couch with legs fully extended, and ankle positioned at approximately 90^o relative to the shank, unsupported and unloaded (32). For the imaging of the VL, participants lay supine with the knee fully extended (anatomical zero) (12, 32). For the VL muscle, the ultrasound derived image was taken at 50% of the distance between the greater trochanter and the lateral epicondyle of the femur (35) and the GM image was taken at 30% of the distance from the popliteal crease to the centre of the lateral malleolus (16). The ultrasound scanning protocol provides moderate to excellent intra-rater reliability in young boys (32). Subsequent analysis of images was carried out using open-source image analysis software (Image J, National Institute of Health, Bethesda, MD, USA) to identify muscle thickness, pennation angle, and fascicle length (32). Each ultrasound image was measured three times, with the average value for each variable used for analysis.

Maximal vertical rebound test: 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. Following the warm-up, participants performed practice attempts of the maximal rebound jump protocol as the principal researcher qualitatively evaluated the task performance competency. Once technical competence was achieved, participants performed the maximal 5-rebound jump test (21) on a force platform (AMTI, Boston, MA) sampling at 1000 Hz. Participants were instructed to stand still for the initial 1 second of the data-collection period (28) to allow for the determination of body weight. Subjects were instructed to keep their hands on their hips whilst aiming to maximise jump height and minimise ground contact time. The first jump in each trial was a countermovement jump, and consequently was excluded for analyses, with the remaining four jumps aggregated and averaged each trial. Within-session reliability was determined using measures quantified from the three rebound jump trials on the same day. For the between-maturity group and correlation analyses, the three trials were averaged and used for further analysis. The raw vertical force–time data for each trial were exported as a text file and analysed using a customised Microsoft Excel spreadsheet via Microsoft Excel for Mac (v.16). Ground reaction force data was smoothed using a fourth order recursive low-pass Butterworth filter with a cut off of 30 Hz and relevant outcomes variables calculated are detailed in *table 2*. Peak force, eccentric and concentric impulse, and eccentric and concentric average power were allometrically scaled to bodyweight to account for the non-linear relationship between muscular strength and body size. Kinetic data and bodyweight were log transformed and then entered into the linear regression models. The beta component of the regression equation was subsequently used as the allometric scaling exponent. A Pearson product moment correlation coefficient was computed to confirm that the scaling exponent sufficiently controlled for bodyweight (7).

***** Table 2 inserted near here *****

Statistical Analyses

Descriptive statistics (means ± standard deviations) were calculated for all maximal rebound jump kinetics for each maturity group. Normality of data were assessed using the Shapiro-Wilk test. Reliability was assessed using a one-way analysis of variance (ANOVA) to test for any systematic bias, intraclass correlation coefficients (ICC) was used for relative reliability, and mean coefficients of variation (CV) used for random error. An ICC greater than 0.75 was used to identify good or excellent reliability (15), with a CV < 10% deemed as acceptable (8).

Between-maturity group differences in force-time variables were assessed using a one-way ANOVA, and post-hoc analysis was used to identify any significantly between-maturity group differences using either Bonferroni or Games-Howell tests, where equal variances were or were not assumed, respectively. Cohen's *d* effect sizes were calculated using pooled standard deviations to establish the magnitude of any between-maturity group differences using the following classifications: trivial < 0.19; small 0.20 – 0.59; 0.60 – 1.19 moderate; 1.20 – 1.99 large; 2.0 – 3.99 very large; > 4.0 extremely large (13). For variables that were not normally distributed, a Mann-Whitney effect size (*r*) was used to assess the magnitude of difference across each variable between maturity groups using the following thresholds: < 0.10 (trivial), 0.10 - 0.29 (small), 0.30 - 0.49 (moderate) and > 0.50 (large).

Relationships between muscle architecture characteristics and maximal rebound jump kinetics for the whole sample were assessed via Pearson's correlation coefficients (*r*) and interpreted using the following classifications: < 0.20 no relationship; 0.20 – 0.44 weak; 0.45 – 0.69 moderate; > 0.70 (30). Stepwise multiple regression analyses were employed to establish the influence of muscle architecture on maximal rebound jump kinetics. All significance values were accepted at $p < 0.05$ and all statistical procedures were conducted using SPSS v.26 for Macintosh.

RESULTS

Within-session reliability

Data for maximal rebound jump kinetics showed moderate to excellent relative reliability (ICC = 0.59 – 0.98) for all maturity groups and acceptable absolute reliability (CV <10%) for contact time, jump height, spring like behaviour, impulse measures, and velocities within the pre-, circa-, and post-PHV cohorts. However, a number of variables across all maturity groups exceeded the acceptance threshold (CV >10%), including RSI, peak GRF, RFD, peak centre of mass (COM) displacement and vertical stiffness (see supplementary *tables 1-3*).

Between-maturity group differences

Between-maturity group differences for maximal rebound jump kinetics are displayed in *table 3.* There were moderate to large, significant differences between all maturity groups for peak GRF, net impulse, braking and propulsive impulse, and eccentric and concentric average power ($d = 0.73 – 2.67$; $p < 0.05$). There were also moderate, significant differences between pre- and circa-, and pre- and post-PHV groups for jump height and RFD ($d = 0.64 – 1.10$; $p < 0.05$), while eccentric velocity had small to moderate significant differences between circa- to post-, and pre- to post-PHV ($d = 0.51$ and 0.83, respectively; $p < 0.05$). RSI, concentric velocity, and peak COM displacement (d = 0.55 - 0.67; p < 0.05). were significantly different only between pre- to post-PHV groups. No significant between-maturity group differences were evidenced for contact time, eccentric time, concentric time, vertical stiffness, and spring like behaviour.

Linear regression of log transformed peak force and bodyweight data computed an allometric scaling component of 0.93 to control for the relationship between body size and relative force ($r = -0.001$; $p > 0.05$). Using the allometrically scaled data, there were no significant differences between maturity groups for relative peak force or relative propulsive impulse. However, relative eccentric and concentric average power, and relative braking impulse were significantly greater in the post-PHV group compared to pre-PHV group ($d = 0.64 - 0.93$; $p < 0.05$).

***** Table 3 inserted near here *****

Relationships between muscle architecture and maximal rebound jump kinetics

Muscle Thickness

Both resting GM and VL muscle thickness demonstrated a weak to moderate association with jump height, peak GRF, total impulse, net impulse, braking impulse, propulsive impulse, eccentric and concentric average power, and eccentric velocity ($r = 0.237 – 0.690$; $p < 0.05$). Additionally, there were moderate, negative relationships between both GM and VL muscle thickness and relative eccentric and concentric velocity ($r = -0.471 - -0.585$; $p < 0.05$).

Pennation Angle

Resting GM pennation angle had weak associations with contact time, jump height, peak GRF, RFD, all absolute impulse measures, eccentric and concentric average power, concentric velocity, and relative braking impulse ($r = 0.230 – 0.440$; $p < 0.05$). Resting VL pennation angle also demonstrated weak associations with total impulse, and braking and propulsive impulse ($r = 0.200 – 0.262$; $p < 0.05$).

Fascicle Length

Resting GM fascicle length showed weak associations with peak GRF, total and net impulse, propulsive impulse, eccentric and concentric average power, and eccentric velocity ($r = 0.200 – 0.351$; $p < 0.05$). Resting VL fascicle length demonstrated a weak association with RSI, peak GRF, total and net impulse, propulsive impulse, eccentric and concentric average power, eccentric velocity, and both relative concentric average power ($r = 0.200 – 0.390$; $p < 0.05$).

Regression Analyses

Muscle thickness alone explained between 38.5-55.8% in peak GRF, absolute impulse variables, and concentric and eccentric average power (see table 4). However, less variance was explained in contact time (GM pennation angle - 6.7%), jump height (VL muscle thickness - 6.1%), RSI (VL fascicle length - 4.2%), RFD (VL muscle thickness – 17.2%) eccentric velocity (VL muscle thickness – 7.3%), concentric velocity (GM pennation angle – 8.5%) and relative measures (3.3-11.2%) (see table 4).

***** Table 4 inserted near here*****

DISCUSSION

The aims of the current study were to investigate maturation effects on maximal rebound jump kinetics and determine the strength of relationships between muscle architecture characteristics and maximal rebound jump kinetics in young boys. Maximal rebound jump kinetics were reduced in the pre-PHV cohort compared with the post-PHV group. Furthermore, the current study found that muscle thickness of the GM or VL predicted the variance (3.3% - 55.8%) of a number of kinetic variables during maximal rebounding in young boys. The current study results indicate that the naturally occurring changes in musculature architecture during maturation are the key determinant to maximal rebounding kinetic performance. Specifically, the majority of kinetic variables were greater in the more mature group compared to the less mature groups, and muscle thickness was the best predictor of a number of these kinetic variables.

Jump height during maximal rebound jumping was reduced in the pre-PHV group compared to the more mature cohorts. Similarly, post-PHV athletes had a greater RSI than the pre-PHV group. However, there were no differences in contact times between the groups, indicating that the increases in RSI were likely due to increased jump heights. While the reliability data from the current study states the CV values for RSI were above the 10% threshold, the differences between the pre- and circa- and pre- and post-PHV groups were larger than the typical error in the quantification of these outcomes, therefore the between-maturity group differences can be interpreted with greater confidence. However, caution should be applied when interpreting rebound jump performance difference in RSI between the circa- and post-PHV groups, as the difference was less than the typical error reported.

While VL muscle thickness explained the greatest amount of variance in jump height, and VL fascicle length was the best predictor of RSI, the explained variance of these were very low (6.7% and 4.2% respectively). These results corroborate prior literature, where VL muscle thickness and fascicle length were significantly correlated with CMJ jump height in post-PHV boys (33). Additionally, VL fascicle length correlates with maximal sprint speed in pre- and post-PHV boys (33). Therefore, these findings may support the notion that VL fascicle length may have limited influence on rapid force production, or force production at high speeds.

Peak GRF, impulse measures, and both eccentric and concentric average power during maximal rebounding were increased across each successive maturity group. The large between group effect relative to typical error in measurement increased confidence with these between-maturity group differences. The differences in rebound performance variables between maturity groups may in part be due to the morphological and neural adaptations that manifest during growth and maturation (9, 32). Force production is generally directly proportional to muscle size (38), which increases as a result of growth and development (16, 32). The assumptions of increased force production due to increased muscle size are supported by the regression analyses from the current study, highlighting the importance of muscle thickness for explaining variance in maximal rebounding kinetics. Specifically, GM muscle thickness explained 36.9% of peak GRF, between 40.2 – 47.2% of variance in net, braking and propulsive impulse, and 36.0% and 32.0% eccentric and concentric average power, respectively. Furthermore, when VL muscle thickness was added to the regression model, the explained variance increased to 44.4% for peak GRF, between 44.6 – 55.8% for impulse variables, 43.3% of eccentric average power and 38.5% of concentric average power. The association between peak force during jumping and muscle thickness of the knee and ankle extensors reported in adolescent surfers (36), showed that lateral gastrocnemius and vastus lateralis thickness predicted 44% and 45% of peak force in a CMJ. Additionally, the relationship between muscle thickness and power output during jumping is similar to previous findings, albeit in adults, where muscle thickness of the gastrocnemius explained 20% of the variance in peak power of a CMJ (11). Cumulatively, the current findings indicate that muscle thickness of the ankle and knee extensors are important determinants for force and power production during jumping tasks in young boys.

RFD was greater in both post- and circa-PHV compared with the pre-PHV group, and these the effect sizes exceeded the typical error reported from the reliability data. Furthermore, VL muscle thickness predicted 17.4% of the variance in RFD. Considering that maximal strength is correlated with RFD (25) and that muscle size influences maximal strength (14, 38), this reported effect is not unexpected. Gastrocnemius thickness is similarly associated with later RFD (30-50 ms) during a drop jump in adults (10). However, it should be noted that in the current study, the explained variance of RFD was relatively low (R^2 = 17.4%) and adding GM muscle thickness to the model only increased the explained variance to ~20%, indicating that there are a number of additional factors that underlie RFD in children, such as tendon stiffness and muscle activation rate (40). Considering that muscles containing longer fascicles may have the capability to produce force at higher shortening velocities due to a greater number of sarcomeres in series (2, 19), the lack of association between fascicle length and RFD is somewhat surprising. The lower association between muscle architecture and RFD may also be due to the greater typical errors associated with RFD which in the current study ranged between 20.4% - 25%. These coefficients of variation are consistent with previous research in young athletes (27). However, in adults, research has highlighted that gastrocnemius fascicle length has an inverse relationship with early RFD (0-10ms) during drop jumps (10). This may be due to series elastic compliance residing largely in the cross-bridges and myofilaments (4), and therefore an increased fascicle length with more cross-bridges may result in greater compliance, which may actually reduce RFD (4).

GM pennation angle explained a small amount of variance in both concentric velocity (8.5%) and contact time (7.2%). Contact time is a surrogate for contraction rate, and the distance moved during that time will determine the velocity. Interestingly, VL muscle thickness explained a small amount of variance in eccentric velocity (7.3%). A faster eccentric velocity increases neuromuscular activation during a SSC due to an increased stretch reflex and musculo-tendon stiffness (10). Therefore, it may be of interest in future studies to identify the relationship between muscle architecture variables and muscle activation properties during maximal rebounding. Ultimately, there was a large amount of unexplained variance in movement velocity. This may be due to a number of factors, including changes in biomechanical strategies. When compared to pre-PHV boys, post-PHV boys increased their ground contact time by ~9%, but COM displacement increased by nearly 30% during this ground contact period, resulting in increased movement velocity. This may reflect changing neuromuscular control strategies with advancing maturation, with more mature subjects favouring longer contact durations to develop an increased net impulse, and greater COM displacement during ground contact to favour increased velocity.

While the majority of absolute measures showed moderate to large differences across maturity in the current cohort of young boys, when these measures were normalized relative to body mass, the differences were reduced. Relative braking impulse, and relative eccentric and concentric average power were all greater in the post-PHV group compared with the pre-PHV group, but there were no differences between maturity groups for relative peak force or relative propulsive impulse. Furthermore, there was limited explained variance in any relative measure (< 11.2%) highlighting that muscle architecture has a fixed influence on relative measure during maximal rebound jumping. Therefore, increases in absolute force, impulse, and power are likely to be most influenced by an increased body mass during maturation in developing young boys.

The findings from the current study demonstrate the importance of the GM during maximal rebounding, as GM muscle architecture was the best predictor of 11 maximal rebounding kinetic variables (6.7% - 47.2%). This is in contrast to the VL, which explained the most variance in six variables, all with a small amount of explained variance (3.3% - 7.8%). The current study results conflicts with previous findings for CMJ performance in young boys, where there was a greater emphasis from musculature around the knee joint (33). Considering that vertical rebounding relies heavily on the *triceps surae* musculature (18), it can be postulated that as athletes mature and develop appropriate musculature at the ankle joint (16, 32), they can begin to utilise distal joint kinetics to a greater effect during maximal rebounding.

The results of this study are one of the first to report differences in maximal rebounding kinetics across various different maturity groups and identified their relationships with muscle architecture variables, however results should be interpreted in light of certain limitations. Considering that muscle geometry is not fixed for a given muscle and dynamic changes occur during a contraction, the visualization of architecture in non-contracted, static muscle may not allow inference of complete muscle function during dynamic, active movements. Therefore, future research may need to study the role of muscle in a more dynamic nature, and the role that this has on SSC performance. Additionally, while the current study provides insight into the relationships between muscle architecture and SSC performance, the effects of training on muscle architecture measures are still unknown and provide a unique opportunity for further research in light of the current study results. highlighting the role that muscle architecture of the GM and VL muscles have on maximal rebounding kinetics in youth.

PRACTICAL APPLICATIONS

The current data indicate that muscle thickness of the GM influences maximal rebounding ability in young boys. Therefore, increasing lower limb muscle mass is an important determinant to positively influence maximal rebounding kinetics in young males. Additionally, the findings suggest that maximal rebounding performance is dictated to a larger extent by the musculature around the ankle joint. From a training perspective, if the goal of training is to increase maximal rebounding performance, it may be prudent for practitioners to include exercises that target the hypertrophy of the gastrocnemius muscle within the training programmes of male youth. While the influence of specific training methods on the development of unique muscle architecture changes is still unknown in paediatric populations, previous studies in adults highlight that heavy resistance training may enhance muscle thickness (3) and hypertrophy in young males.

REFERENCES

1. Addie CD, Arnett JE, Neltner TJ, Straughn MK, Greska EK, Cosio-Lima L, and Brown LE. Effects of Drop Height on Drop Jump Performance. *International Journal of Kinesiology and Sports Science* 7, 2019.
2. Blazevich. Effects of Physical Training and Detraining, Immobilisation, Growth and Aging on Human Fascicle Geometry. *Sports Med* 36: 1003-1017, 2006.
3. Blazevich AJ, Cannavan D, Coleman DR, and Horne S. Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. *J Appl Physiol (1985)* 103: 1565-1575, 2007.
4. Blazevich AJ, Cannavan D, Horne S, Coleman DR, and Aagaard P. Changes in muscle force-length properties affect the early rise of force in vivo. *Muscle Nerve* 39: 512-520, 2009.
5. Blazevich AJ and Sharp NC. Understanding muscle architectural adaptation: macro- and micro-level research. *Cells Tissues Organs* 181: 1-10, 2005.
6. Cinemre A, Unver E, Konsuk Unlu H, and Demirci N. A Comparison of Drop Jump and Sprint Parameters in Youth Soccer Players. *Turkish Journal of Sports Medicine* 55: 148-155, 2020.
7. Cleather DJ. Adjusting powerlifting performances for differences in body mass. *J Strength Cond Res* 20: 412-421, 2006.

8. Cormack SJ, Newton RU, McGuigan MR, and Doyle LA. Reliability of Measures Obtained During Single and Repeated Countermovement Jumps. *International Journal of Sports Physiology and Performance* 3: 131-144, 2008.
9. Dotan R, Mitchell C, and R. C. Child-Adult differences in muscle activation - a review. *Pediatric Exercise Science* 24: 20, 2012.
10. Earp JE, Kraemer WJ, Cormie P, Volek JS, Maresh CM, Joseph M, and Newton RU. Influence of muscle-tendon unit structure on rate of force development during the squat, countermovement, and drop jumps. *Journal of Strength and Conditioning Research* 25: 340-347, 2011.
11. Earp JE, Kraemer WJ, Newton RU, Comstock BA, Fragala MS, Dunn-Lewis C, Solomon-Hill G, Penwell ZR, Powell MD, Volek JS, Denegar CR, Hakkinen K, and Maresh CM. Lower-body muscle structure and its role in jump performance during squat, countermovement, and depth drop jumps. *J Strength Cond Res* 24: 722-729, 2010.
12. Franchi MV, Longo S, Mallinson J, Quinlan JI, Taylor T, Greenhaff PL, and Narici MV. Muscle thickness correlates to muscle cross-sectional area in the assessment of strength training-induced hypertrophy. *Scand J Med Sci Sports* 28: 846-853, 2018.
13. Hopkins WG, Marshall SW, Batterham AM, and Hanin J. Progressive Statistics for Studies in Sports Medicine and Exercise Science. *Med Sci in Sports Ex* 41: 3-12, 2009.
14. Jones EJ, Bishop PA, Woods AK, and Green JM. Cross-Sectional Area and Muscular Strength: A Brief Review. *Sports Med* 38: 987-994, 2008.
15. Koo TK and Li MY. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *J Chiropr Med* 15: 155-163, 2016.
16. Kubo K, Teshima T, Hirose N, and Tsunoda N. A cross-sectional study of the plantar flexor muscle and tendon during growth. *Int J Sports Med* 35: 828-834, 2014.
17. Kubo K, Teshima T, Ikebukuro T, Hirose N, and Tsunoda N. Tendon properties and muscle architecture for knee extensors and plantar flexors in boys and men. *Clin Biomech* 29: 506-511, 2014.
18. Lamontagne M and Kennedy MJ. The biomechanics of vertical hopping: a review. *Res Sports Med* 21: 380-394, 2013.
19. Lieber RL and Ward SR. Skeletal muscle design to meet functional demands. *Philos Trans R Soc Lond B Biol Sci* 366: 1466-1476, 2011.
20. Lloyd RS, Oliver JL, Hughes MG, and Williams CA. The influence of chronological age on periods of accelerated adaptation of stretch-shortening cycle performance in pre and postpubescent boys. *J Strength Cond Res* 25: 1889-1897, 2011.
21. Lloyd RS, Oliver JL, Hughes MG, and Williams CA. Specificity of test selection for the appropriate assessment of different measures of stretch-shortening cycle function in children. *J Sports Med Phys Fitness* 51: 595-602, 2011.
22. Lloyd RS, Oliver JL, Hughes MG, and Williams CA. Age-related differences in the neural regulation of stretch-shortening cycle activities in male youths during maximal and sub-maximal hopping. *J Electromyogr Kinesiol* 22: 37-43, 2012.
23. Lloyd RS, Oliver JL, Hughes MG, and Williams CA. The effects of 4-weeks of plyometric training on reactive strength index and leg stiffness in male youths. *J Strength Cond Res* 26: 2812-2819, 2012.
24. Meyers RW, Oliver JL, Hughes MG, Cronin JB, and Lloyd RS. Maximal sprint speed in boys of increasing maturity. *Pediatr Exerc Sci* 27: 85-94, 2015.
25. Mirkov DM, Nedeljkovic A, Milanovic S, and Jaric S. Muscle strength testing: evaluation of tests of explosive force production. *Eur J Appl Physiol* 91: 147-154, 2004.

26. Mirwald RL, Baxter-Jones AD, Bailey DA, and Beunen G. An assessment of maturity from anthropometric measurements. *Physcial Fitness and Performance* 34: 689–694, 2002.
27. Moeskops S, Oliver JL, Read PJ, Cronin JB, Myer GD, Haff GG, and Lloyd RS. Within- and between-session reliability of the isometric mid-thigh pull in young female athletes. *Journal of Strength and Conditioning Research* 32: 1892-1901, 2018.
28. Moir GL. Three Different Methods of Calculating Vertical Jump Height from Force Platform Data in Men and Women. *Meas Phys Educ Exerc Sci* 12: 207-218, 2008.
29. Nicol C, Avela J, and Komi PV. The stretch-shortening cycle a model to study naturally occurring neuromuscular fatigue. *Sports Med* 36: 977-999, 2006.
30. O'Donoghue P. *Statistics for Sport and Exercise Studies: an introduction.* London: Routledge, 2012.
31. Payne S, Townsend N, and Foster C. The physical activity profile of active children in England. *Int J Behav Nutr Phy*: 1-8, 2013.
32. Radnor JM, Oliver JL, Waugh CM, Myer GD, and Lloyd RS. The Influence of Maturity Status on Muscle Architecture in School-Aged Boys. *Pediatr Exerc Sci*, 32(2), 89-96, 2020.
33. Radnor JM, Oliver JL, Waugh CM, Myer GD, and Lloyd RS. Muscle architecture and maturation influences sprint and jump ability in young boys: a multi-study approach. *Journal of Strength and Conditioning Research*, 2021.
34. Radnor JM, Oliver JL, Waugh CM, Myer GD, Moore IS, and Lloyd RS. The Influence of Growth and Maturation on Stretch-Shortening Cycle Function in Youth. *Sports Med* 48: 57-71, 2018.
35. Secomb JL, Lundgren LE, Farley OR, Tran TT, Nimphius S, and Sheppard JM. Relationships Between Lower-Body Muscle Structure and Lower-Body Strength, Power, and Muscle-Tendon Complex Stiffness. *J Strength Cond Res* 29: 2221-2228, 2015.
36. Secomb JL, Nimphius S, Farley OR, Lundgren LE, Tran TT, and Sheppard JM. Relationships between lower-body muscle structure and, lower-body strength, explosiveness and eccentric leg stiffness. *J sports sci med* 14: 691-697, 2015.
37. Temfemo A, Hugues J, Chardon K, Mandengue SH, and Ahmaidi S. Relationship between vertical jumping performance and anthropometric characteristics during growth in boys and girls. *Eur J Pediatr* 168: 457-464, 2009.
38. Tonson A, Ratel S, Le Fur Y, Cozzone P, and Bendahan D. Effect of maturation on the relationship between muscle size and force production. *Med Sci Sports Exerc* 40: 918-925, 2008.
39. Waugh CM, Korff T, and Blazevich AJ. Developmental differences in dynamic muscle-tendon behaviour: implications for movement efficiency. *J Exp Biol* 220: 1287-1294, 2017.
40. Waugh CM, Korff T, Fath F, and Blazevich AJ. Rapid force production in children and adults: mechanical and neural contributions. *Med Sci Sports Exerc* 45: 762-771, 2013.

ACKNOWLEDGMENTS

No sources of funding were used to assist in the preparation of this article. One author acknowledges funding support from National Institutes of Health Grants. Four of the authors

declare that they have no conflicts of interest relevant to the content of this review. One author declares that they receive book royalties on topics related to the manuscript.

Table 1. Descriptive statistics for all anthropometric variables for the pre-PHV, circa-PHV and post-PHV groups (mean ± SD)

	Pre-PHV (n = 45)	Circa-PHV (n = 25)	Post-PHV (n = 29)
Age (years)	12.47 ± 0.54	13.85 ± 0.75	15.76 ± 0.82
Standing Height (cm)	153.16 ± 6.53	167.14 ± 5.12	177.57 ± 6.08
Leg Length (cm)	75.92 ± 5.00	82.09 ± 4.38	83.89 ± 4.17
Body Mass (kg)	42.59 ± 6.40	56.88 ± 9.13	72.83 ± 12.89
Maturity Offset (years)	-1.67 ± 0.44	-0.01 ± 0.28	2.07 ± 0.61

Table 2. Method of calculation for all maximal rebound jumping kinetics

VARIABLE	METHOD OF CALCULATION
Ground Contact Time (s)	Take-off and landing points were identified as the first data point recorded greater than 15 N (initial ground contact) and the final data point above 15 N (take-off). Using these time points, the "noise" of the flight time force was calculated. A threshold of 5*SD was calculated and this was used as the threshold for determining actual take-off and landing. The duration of time between landing and take-off was defined as 'ground contact time'
Jump Height (m)	Defined as the largest vertical displacement of the body's centre of mass during the flight time between the first and second ground contact $= \text{TOV}^2/2g$ (TOV = take off velocity; g = acceleration due to gravity)
Reactive Strength Index	Calculated as the ratio of jump height (mm) and ground contact time (ms)
Peak Ground Reaction Force (N)	Calculated as the highest force peak during each maximal hop
Peak Instantaneous Rate of Force Development (N/s)	Defined as the 0.001 s interval that had the greatest change in force between initial ground contact and the occurrence of the first peak.
Total Impulse (N.s)	Total vertical impulse applied to the ground during ground contact is calculated by summing the instantaneous impulse values (force x time) for the duration of the ground contact during each hop.
Net Impulse (N.s)	Net vertical impulse is the difference produced by subtracting body weight impulse from the total vertical impulse.
Braking Impulse (Ns)	Braking impulse (is the total vertical impulse applied to the ground during the landing phase of ground contact and is calculated by summing the instantaneous impulse values between initial ground contact and peak centre of mass displacement.
Propulsive Impulse (Ns)	Concentric impulse is the total vertical impulse applied to the ground during the take-off phase of ground contact and is calculated by summing the instantaneous impulse values between peak centre of mass displacement and take-off.

Eccentric Average Power (W)	Velocity of the centre of mass was multiplied by the ground reaction force at each timing sample to derive power. Mean eccentric power was calculated as the average power between initial ground contact and the timing of the maximal displacement of centre of mass.
Concentric Average Power (W)	Velocity of the centre of mass was multiplied by the ground reaction force at each timing sample to derive power. Mean concentric power was calculated as the average power from the timing of lowest point of the centre of mass and the point of take-off.
Spring like Correlation (*r*)	Determined by calculating a Pearson’s correlation of coefficient using centre of mass displacement and absolute vertical force throughout the initial ground contact.
Vertical Stiffness (KN/m)	Vertical stiffness is calculated as the ratio of peak vertical ground reaction force during the first landing to maximal vertical displacement of the centre of mass. Since the calculation of stiffness relies on the assumption that an individual is displaying spring-like characteristics and that peak force and peak displacement occur at the same time, previous literature has utilised a threshold of -0.8 for the Pearson correlation between vertical force and vertical displacement to indicate spring-like behaviour. If the Pearson correlation is greater than -0.8 then stiffness is not calculated.
Peak Centre of Mass Displacement (m)	Determined by dividing the vertical component of the ground reaction force by the participant’s body mass to determine acceleration. Double integration of acceleration was then performed to calculate displacement of centre of mass.
Relative peak Ground Reaction Force (N/kg)	Peak ground reaction force divided by allometrically scaled body mass
Relative Braking Impulse (N.s/kg)	Braking impulse divided by allometrically scaled body mass
Relative Propulsive Impulse (N.s/kg)	Propulsive impulse divided by allometrically scaled body mass
Relative Eccentric Average Power (W/kg)	Eccentric average power divided by allometrically scaled body mass
Relative Concentric Average Power (W/kg)	Concentric average power divided by allometrically scaled body mass

Table 3. Differences in maximal rebounding kinetics across maturity groups

	PRE	**CIRCA**	**POST**	**EFFECT SIZE (*d*)**		
	Mean ± SD	Mean ± SD	Mean ± SD	PRE - CIRCA	CIRCA - POST	PRE - POST
Contact time (s)	0.23 ± 0.07	0.24 ± 0.07	0.25 ± 0.09	0.11	0.13	0.23
Jump height (m)	0.21 ± 0.05	0.25 ± 0.05*	0.28 ± 0.08*	0.74	0.44	0.99
RSI	1.00 ± 0.28	1.14 ± 0.37	1.25 ± 0.49*	0.45	0.24	0.63
Peak GRF (N)	2162 ± 481	2964 ± 772*	3666 ± 821*#	1.10	0.73	1.99
Peak Instantaneous RFD (N/s)	56939 ± 22488	77021 ± 23535*	90327 ± 28660*	0.81	0.49	1.12
Total Impulse (N.s)	266.8 ± 51.3	379.6 ± 69.6*	516.8 ± 134.0*#	1.42	1.07	1.63
Net Impulse (N.s)	171.6 ± 25.4	249.4 ± 45.7*	338.5 ± 80.8*#	1.54	1.11	1.70
Braking Impulse (N.s)	122.9 ± 27.8	179.1 ± 31.2*	249.0 ± 69.8*#	1.42	1.08	1.61
Propulsive Impulse (N.s)	145.0 ± 29.7	205.7 ± 48.3*	272.6 ± 69.0*#	1.22	0.98	1.58
Peak CoM displacement (m)	0.14 ± 0.05	0.17 ± 0.05	0.18 ± 0.06*	0.50	0.32	0.76
Spring like behaviour	0.92 ± 0.07	0.91 ± 0.10	0.93 ± 0.06	-0.18	0.27	0.13
Vertical Stiffness (kN/m)	19.38 ± 10.84	23.35 ± 10.28	24.25 ± 12.09	0.37	0.08	0.42
Eccentric Average Power (W)	1417 ± 292	2102 ± 600*	2895 ± 881*#	1.33	0.92	2.15
Concentric Average Power (W)	1399 ± 324	2102 ± 662*	2897 ± 703*#	1.23	0.79	1.83
Eccentric Velocity (m/s)	1.06 ± 0.14	1.11 ± 0.17*	1.22 ± 0.19*	0.27	0.51	0.83
Concentric Velocity (m/s)	1.19 ± 0.21	1.32 ± 0.26	1.36 ± 0.26*	0.49	0.13	0.64
Relative peak GRF (N/kg$^{0.93}$)	66.10 ± 11.59	69.00 ± 13.64	68.86 ± 15.44	0.19	-0.01	0.17

Relative braking impulse (N.s/ kg$^{0.93}$)	3.76 ± 0.65	4.21 ± 0.65	4.57 ± 0.81*	0.57	0.42	0.93
Relative propulsive impulse (N.s/ kg$^{0.93}$)	4.61 ± 0.79	4.82 ± 0.96	5.05 ± 0.95	0.20	0.20	0.42
Relative eccentric average power (W/ kg$^{0.93}$)	43.55 ± 8.11	49.05 ± 11.78	53.95 ± 14.56*	0.47	0.31	0.79
Relative concentric average power (W/ kg$^{0.93}$)	43.23 ± 9.79	49.23 ± 13.93	54.40 ± 20.44*	0.43	0.26	0.64

RSI: Reactive strength index; GRF: ground reaction force; RFD: Rate of force development; CoM: centre of mass

*significantly greater than pre-PHV

significantly greater than circa-PHV

Table 4. Explained variance of maximal hopping kinetics from muscle architecture variables

Dependent Variable	**Model Number**	**Independent Variable**	***Adjusted R^2*** **(%)**	**Model *p* value**
Peak GRF (N)	1	GMMT	36.9	< 0.001
	2	GMMT + VLMT	44.4	< 0.001
Peak Instantaneous RFD ($N.s^{-1}$)	1	VLMT	17.4	< 0.001
	2	VLMT + GMMT	19.8	0.032
Net Impulse (N.s)	1	GMMT	47.2	< 0.001
	2	GMMT + VLMT	55.8	< 0.001
Braking Impulse (N.s)	1	GMMT	40.2	< 0.001
	2	GMMT + VLMT	44.6	0.001
	3	GMMT + VLMT + GMFL	47.4	0.007
	4	GMMT + VLMT + GMFL + VLFL	48.9	0.032
Propulsive Impulse (N.s)	1	GMMT	42.1	< 0.001
	2	GMMT + VLMT	48.7	0.001
Eccentric Average Power (W)	1	GMMT	36.0	< 0.001
	2	GMMT + VLMT	43.3	< 0.001
Concentric Average Power (W)	1	GMMT	32.0	< 0.001
	2	GMMT + VLMT	38.5	0.001
Eccentric Velocity (m/s)	1	VLMT	7.3	0.001
Concentric Velocity (m/s)	1	GMPA	8.5	0.001
Relative Braking Impulse (N.s/kg)	1	GMPA	11.2	< 0.001
Relative Eccentric Average Power (W/kg)	1	VLMT	3.3	0.022
Relative Concentric Average Power (W/kg)	1	VLFL	7.8	0.001

GM: Gastrocnemius Medialis; VL: Vastus Lateralis; MT: Muscle Thickness; PA: Pennation Angle; FL: Fascicle Length