

1 **TITLE:**

2 THE INFLUENCE OF MATURITY STATUS ON MUSCLE ARCHITECTURE IN
3 SCHOOL-AGED BOYS

4

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30 ABSTRACT

31 **Purpose:** To determine the differences in muscle architecture of the lower limb in pre-, circa-
32 and post-peak height velocity (PHV) boys. **Methods:** Muscle architecture variables from both
33 the gastrocnemius medialis (GM) and vastus lateralis (VL) were derived from ultrasonographic
34 images in 126 school-boys. One-way ANOVA's using Bonferonni post-hoc comparisons were
35 employed to determine between-group differences and effect sizes were calculated to establish
36 the magnitude of these differences. **Results:** All muscle architecture variables showed
37 significant small to large increases from pre- to post-PHV, excluding GM fascicle length ($d =$
38 $0.59 - 1.39; p < 0.05$). More discrete between-group differences were evident as GM and VL
39 muscle thickness and physiological thickness significantly increased between pre- and circa-
40 PHV ($d > 0.57; p < 0.05$); however only the VL muscle thickness and physiological thickness
41 increased from circa- to post-PHV ($d = 0.68; p < 0.05$). The post-PHV group also showed larger
42 GM pennation angles than the circa-PHV group ($d = 0.59; p < 0.05$). **Conclusion:** The
43 combined results show that maturation is associated with changes in muscle morphology.
44 These data quantify the maturity-related changes in muscle architecture variables provide a
45 reference to differentiate between training induced adaptations versus changes associated with
46 normal growth and maturation.

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55 INTRODUCTION

56 Notable disparities in anatomy and physiology exist between children and adults, and there are
57 also clear differentiations between children and adolescents, mediated by growth and
58 maturation (23, 35). Force-producing capacities are lower in children when compared to
59 adolescents or adults, partly as a result of the architecture and size of the muscle (18, 20, 30)
60 and specific muscle activation patterns (9). Throughout maturation, the neuromuscular system
61 develops in a non-linear manner, resulting in large variations in physical performances of
62 children of similar chronological age (26). It is known that maturity leads to increased body
63 mass and fat free mass (23), however, the specific structural adaptations that occur naturally
64 throughout growth and maturation are yet to be fully understood. Very few studies have
65 specifically examined how muscle size changes throughout childhood and adolescence, and
66 how the maturation process may result in specific architectural changes. Considering that
67 muscle architecture is an important factor when it comes to determining a muscle's function
68 and influences both force production and contraction velocity (21), examining maturity-related
69 developmental changes in muscle architecture is warranted.

70 Muscle architecture is typically characterised by parameters such as fascicle length,
71 pennation angle and cross-sectional area (5). Despite fascicular arrangements significantly
72 influencing a muscle function (7), particularly the fascicle's force-length and force-velocity
73 characteristics (36), age- and maturity-related comparisons of muscle architecture measures
74 between adults, adolescents, and children are sparse. Research suggests that adults demonstrate
75 greater muscle thickness than children (19, 29) while older adolescents exhibit greater muscle
76 thickness relative to their younger peers (17, 18). Men have been shown to have longer fascicles
77 than boys, and this remains the same for fascicle length when made relative to thigh length
78 (20). Furthermore, 15-year-old adolescents have been shown to possess significantly longer
79 muscle fascicles than children, but do not differ from adults (17), implying that fascicle length

80 reaches adult levels at or before the age of 15 years. Pennation angle of the knee extensor
81 muscles seems to remain consistent from childhood through to adulthood (17), whereas the
82 pennation angle of the gastrocnemius medialis has been reported to increase from birth before
83 becoming stable following the adolescent growth spurt (3, 14). However, maturational status
84 was not quantified in these studies, and the developmental effects on pennation angle
85 throughout maturation is still unknown. The existing literature has focused on changes based
86 on chronological age as opposed to grouping according to maturity status. Therefore, the
87 manner in which muscle architecture changes throughout the non-linear process of
88 maturational development remains unclear.

89 Literature has demonstrated that individuals of the same chronological age can differ
90 markedly with respect to biological maturity (1). Furthermore, significant inter-individual
91 variation exists for the level (magnitude of change), timing (onset of change), and tempo (rate
92 of change) of maturation. Therefore, it is important to quantify muscle architecture in relation
93 to maturity status as opposed to chronological age. Understanding how muscle architecture
94 variables differ between maturity groups would better enable researchers to distinguish
95 between changes caused by growth and maturation versus those mediated by physical training.
96 Additionally, the majority of previous studies have compared a single age group during
97 childhood versus adults and given that maturation is non-linear, the comparison of two discrete
98 age groups does not highlight how muscle architecture changes throughout the fluctuating
99 process of maturation (17, 20, 30). Finally, it should be noted that the majority of previous
100 studies have not included children coincident with peak height velocity (PHV) which, due to
101 the rapid gains in height and mass, is regarded as a unique stage of development within
102 paediatric populations and can have significant effects on muscle architecture due to the
103 differential lengthening of bone and muscle during this period.

104 Therefore, the aim of the current study was to investigate differences in muscle
105 thickness, pennation angle, and fascicle length of vastus lateralis and gastrocnemius medialis
106 of pre-, circa- and post-PHV boys. We hypothesised that muscle thickness, pennation angle,
107 and fascicle length would increase across maturity groups, with the largest differences evident
108 between the circa- and post-PHV groups.

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110 METHOD

111 **Participants**

112 One hundred and eighty-three male secondary school children in the United Kingdom
113 volunteered to participate in the study. Sample size was estimated *a priori* using statistical
114 software (G*Power v 3.1) for the analyses of variance test, considering an effect size of 0.4,
115 significance level of 0.05, and statistical power of 0.95, for the primary outcome variables of
116 muscle thickness, pennation angle and fascicle length, a sample size of 102 was needed. All
117 participants were free from lower extremity injury and were involved in regular sport and
118 physical education-based activity programs, inclusive of strength and conditioning and games-
119 based activities. Participants were asked to refrain from strenuous exercise at least 48 hours
120 prior to testing. Written parental consent and participant's assent were then obtained for
121 participants under 18 years prior to involvement in the study, while ethical approval was
122 granted by the Cardiff School of Sport Research Ethics Committee.

123

124 **Procedures**

125 *Anthropometrics:* Standing height (centimetres) and seated height (centimetres) were measured
126 using a stadiometer (SECA 321, Vogel and Halke, Germany), and body mass (kilograms) was
127 measured using a balance beam scale (SECA 770, Vogel and Halke, Germany). Biological
128 maturity was then determined using years from PHV (28). Maturity offset values were

129 calculated using the sex-specific equation for boys: $- [9.236 + 0.0002708 \cdot \text{Leg Length and}$
130 $\text{Sitting Height interaction}] - [0.001663 \cdot \text{Age and Leg Length interaction}] + [0.007216 \cdot \text{Age and}$
131 $\text{Sitting Height interaction}] + [0.02292 \cdot \text{mass by Height ratio}]$. Due to the error in the prediction
132 equation of approximately 6 months for boys (16), participants with a maturity offset of -1 to
133 -0.5 years, and +0.5 to +1 years were removed from the study. Additionally, participants whose
134 maturity offset was outside -3 or + 3 years were also removed from the study to maximise
135 accuracy. These selection criteria resulted in 57 participants being removed from the study.
136 The final sample size was 126 subjects, which was still above the required number from the
137 sample size analysis. This robust approach enabled the identification of three distinct maturity
138 groups: pre-PHV group (maturity offset of < -1), circa-PHV (maturity offset between $-0.5 -$
139 0.5), and post-PHV group (maturity offset of > 1). Descriptive statistics for each age group are
140 presented in *table 1*.

141

142 *******Table 1 inserted here *******

143

144 *Muscle architecture:* Muscle structure of the gastrocnemius medialis (GM) and vastus lateralis
145 (VL) were measured with real time B-Mode ultrasonography (Vivid E9, GE Healthcare,
146 Chalfont St Giles, UK) with a 45-mm linear array probe. Water soluble gel was applied to both
147 the ultrasound probe and the participants' skin for acoustic coupling, to enhance the contrast
148 of the images, and to avoid depression of the dermal layer. To measure the GM, participants
149 laid prone on a massage couch with the hip angle at approximately 180° relative to the trunk,
150 the knee set at approximately 180° relative to the thigh, and ankle positioned at approximately
151 90° relative to the shank. For the imaging of the VL, participants lay supine with the hip
152 positioned at 90° relative to the trunk, and legs fully extended. For both muscles, the ultrasound
153 probe was placed perpendicular to the skin, and the scanning surface was orientated until it was

154 positioned parallel to the muscle to collect sagittal plane images of each subject's dominant
155 leg. For the VL muscle, the image was taken at 50% of the distance between the greater
156 trochanter and the lateral epicondyle of the femur (33) and the GM image was taken at 30% of
157 the distance from the popliteal crease to the centre of the lateral malleolus (18). The subsequent
158 analysis was carried out using open-source image analysis software (Image J, National Institute
159 of Health, Bethesda, MD, USA) to calculate pennation angle, fascicle length and muscle
160 thickness. *Figure 1* depicts how the muscle architecture characteristics were calculated. Muscle
161 thickness was measured as the distance from the superficial aponeuroses to the deep
162 aponeuroses. The thickness of the proximal, distal and middle of the muscle belly was assessed
163 in the image, and the average of these sites used for further analysis. Physiological muscle
164 thickness was calculated by the following equation: $(\text{muscle thickness}^2 + [\tan \times \text{pennation angle}$
165 $\times \text{muscle thickness}]^2)^{0.5}$ (6). Pennation angle (Θ_p) was defined as the angle between the muscle
166 fascicles and the deep aponeuroses. As the entire fascicle was not visible in the ultrasound
167 image, it was calculated from the equation: $\text{fascicle length} = \text{muscle thickness} (\sin \Theta_p)^{-1}$ (6).
168 Each ultrasound image was assessed on three occasions, with the average value for each
169 architectural variable used for analysis.

170

171 *******Figure 1 inserted here *******

172

173 Figure 1. Ultrasound image of the gastrocnemius medialis, highlighting how the muscle
174 architecture variables were calculated. MT: muscle thickness; PA: pennation angle;
175 FL: fascicle length

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178 **Reliability**

179 To establish intra-rater reliability of the ultrasonographic measurements, a sub-group of thirty-
180 four school aged boys (14 = pre-PHV, 20 = post-PHV) attended a test session, where three
181 images were taken for each muscle. Subsequently, two levels of reliability were quantified for
182 each muscle architecture variable. *Within-image reliability* reflected the reliability of digitising
183 an image and was assessed using three measurements of each variable in the final image taken
184 during the test session. *Between-image reliability* determined the reliability of taking accurate
185 images of the same muscle site, and was assessed by calculating an average measure from the
186 three trials of each muscle architecture variable from each of the three images within the test
187 session.

188

189 **Statistical Analysis**

190 Within-image and between-image reliability for each variable was determined using mean
191 coefficients of variation (CV%), intraclass correlation coefficients (ICC) and the change in
192 mean. Magnitudes of ICC were classified according to the following thresholds: Poor < 0.49;
193 Moderate 0.5 – 0.74; Good 0.75 – 0.89; Excellent > 0.9 [18]. All reliability statistics were
194 calculated using an online spreadsheet run through Microsoft Excel for Mac version 16.3 (11).

195 Descriptive statistics (means \pm standard deviations) were calculated for all muscle
196 architecture variables for each maturity group. Differences in muscle architecture variables
197 between maturity groups and across both muscles were assessed using a 3 x 2 (maturity group
198 x muscle) mixed model ANOVA. Homogeneity of variance was assessed via Levene's statistic
199 and where violated, Welch's adjustment was used to correct the F-ratio. Post-Hoc analysis was
200 used to identify the groups that were significantly different to one another using either
201 Bonferroni or Games-Howell post-hoc analysis, where equal variances were and were not
202 assumed, respectively. Cohen's *d* effect sizes were also calculated, using pooled standard
203 deviations to establish the magnitude of any between-group differences using the following

204 classifications: : trivial < 0.19; small 0.2 – 0.59; moderate 0.6 – 1.19; large 1.2 – 1.9; very large
205 2.0 – 3.9; > extremely large > 4.0 (12). The strength of relationships between muscle
206 architecture variables in the whole sample, and when sub-divided by maturity group (pre-PHV
207 vs circa-PHV vs post-PHV) were assessed using Pearson’s correlation coefficient, and
208 interpreted as: < 0.2 no relationship; 0.2 – 0.45 weak; 0.45 – 0.7 moderate; > 0.7 strong based
209 on previous recommendations (31). All significance values were accepted at $p \leq 0.05$ and all
210 statistical procedures were conducted using SPSS v.23 for Macintosh.

211

212 RESULTS

213 **Reliability of ultrasonography**

214 Data for all architectural variables in both muscle sites showed excellent ICC and acceptable
215 CV% for within-image reliability in both maturity groups (pre-PHV: ICC = 0.87 – 1.00; CV =
216 0.9 – 7.1%, post-PHV: ICC = 0.92 – 1.00; 0.6 – 3.1%). Apart from VL fascicle length in the
217 pre-PHV cohort, all architectural variables ICC’s for between-images indicated moderate to
218 excellent reliability and acceptable CV % for both muscle sites in the pre-PHV (ICC = 0.59 –
219 0.97; CV = 3.3 – 11.1%) and post-PHV groups (ICC = 0.75 – 0.95; CV= 2.9 – 5.9%).

220

221 **Between-group differences in muscle architecture**

222 Muscle architecture variables for pre-, circa- and post-PHV groups are displayed in *figure 2a-*
223 *e*. For GM muscle thickness and physiological thickness, there was a moderate, significant
224 difference between the pre- and post-PHV groups ($d = 1.19$ and 1.12 ; $p < 0.05$), respectively);
225 and also small to moderate, significant differences between the pre- and circa-PHV cohorts (d
226 = 0.96 and 0.57 ; $p < 0.05$, respectively). There were moderate, significant differences for GM
227 pennation angle between the post-PHV and both the pre- and circa-PHV groups ($d = 0.94$ and
228 0.59 , respectively; $p < 0.05$). However, there was no significant difference in GM fascicle

229 length between any groups. For VL muscle thickness and physiological thickness there were
230 moderate to large, significant differences between the pre- and post-PHV groups, pre- and
231 circa-PHV, and circa- to post-PHV cohorts ($d = 0.68 - 1.40$, respectively). For both VL
232 pennation angle and fascicle length, there were significant differences between the pre-PHV
233 and the post-PHV group ($d = 0.59$ and 0.66 , respectively; $p < 0.05$), but no differences between
234 any other groups. When made relative to leg length, there was no difference between groups
235 for fascicle length for either GM or VL muscles.

236 With regards to differences in architectural variables between muscles, both VL muscle
237 thickness and fascicle length were significantly greater than GM muscle thickness and fascicle
238 length ($p < 0.001$) in the pre-, circa- and post-PHV groups. Contrastingly, for all maturity
239 groups, GM pennation angle was significantly greater than VL pennation angle ($p < 0.001$).

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*****Figure 2 a-e inserted here *****

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243 Figure 2. Differences between pre-, circa-, and post-PHV groups in a) physiological muscle
244 thickness, b) muscle thickness, c) pennation angle, d) fascicle length, and e) relative
245 fascicle length

246

* significant difference between groups ($p < 0.05$). $d =$ Cohen's effect size.

247

248 For both the GM and VL muscle, data showed significant, weak correlations between
249 thickness and pennation angle for the whole group, and the pre- and post-PHV group ($r = 0.28$
250 $- 0.43$; $p < 0.05$). Additionally, the relationship between both GM and VL muscle thickness
251 and fascicle length showed weak to strong, significant relationships across the whole group,
252 and the three maturity groups ($r = 0.37 - 0.76$; $p < 0.05$). Finally, there were significant,

253 moderate to strong, negative correlations between GM and VL pennation angle and fascicle
254 length in all the groups ($r = -0.51$ to -0.79 ; $p < 0.05$).

255

256 DISCUSSION

257 The initial hypothesis can be accepted, as the results showed an increase in GM and VL muscle
258 thickness, GM and VL pennation angle, and VL fascicle length from pre- to post-PHV.

259 However, the larger differences in muscle architecture variables were seen between the pre-
260 and circa- PHV groups. In light of existing literature, this appears to be the first study to
261 compare muscle architecture variables across all maturity stages in in a sample of male youth.

262 While previous literature has compared circa- and post-PHV groups with adults, this is the first
263 study to examine a pre-PHV cohort. The main findings of the current study showed that all
264 muscle architecture variables showed significant small to large increases from pre- to post-
265 PHV with the exception of GM fascicle length. More discrete between-group differences were
266 evident as GM and VL muscle thickness and physiological thickness significantly increased
267 between pre- and circa-PHV; however only the VL muscle thickness and physiological
268 thickness increased from circa- to post-PHV. The post-PHV group also showed larger GM
269 pennation angles than the circa-PHV group. Finally, for both the VL pennation angle and
270 fascicle length, there were small to moderate, significant differences between the pre-PHV and
271 post-PHV groups, but no differences between any other groups.

272 The current study showed that GM muscle thickness increases from pre-PHV to both
273 circa-PHV and post-PHV. For both maturity groups, these changes in muscle thickness were
274 larger than the typical error (CV%), and are therefore considered as meaningful changes likely
275 due to maturation as opposed to merely reflecting noise in the measurement. The non-
276 significant change between circa- and post-PHV groups would indicate that natural
277 developments in GM muscle thickness may have started to stabilise around the time of PHV.

278 Growth of the muscle throughout maturation may occur due to increases in body mass
279 potentially through increases in skeletal mass, and internal organs intensifying the mechanical
280 load on the skeletal system during everyday tasks (5). Additionally, changes in stature will
281 enhance muscle growth as the load or stretch applied to muscles during bone growth may act
282 as a stimulus for increases in muscle size (37). Previous studies, albeit examining age-related
283 differences, have shown significant increases in GM muscle thickness between elementary
284 school children, junior school children, and adults (18). The differences between adults and
285 junior school children suggest that there may be further development of muscle size during
286 ageing, beyond that of adolescence. This could be due to large changes in activity profile and
287 body mass during adulthood driving increases in mechanical loading that underpin the
288 mechanism of muscle growth (5). Data from Binzoni and colleagues (3) showed approximate
289 increases in GM muscle thickness of 7% per year, which was then confirmed in an empirical
290 study with children between the ages of 5 -12 years (2). Expressing results from the current
291 study by chronological age as opposed to maturity, shows an approximate 9% increase in GM
292 muscle thickness per year between 12 years to 14 years, but only a 5% increase per year
293 between 14 to 16 years. Cumulatively, these results support the notion of a slower rate of
294 growth in the GM muscle following PHV, which may infer that further maturity-related
295 increases in lower limb strength (27) may be due to growth of different muscles or ongoing
296 changes in neural properties (9). For example, as children mature they have a greater potential
297 to produce force, as there is a reduced agonist– antagonist co-contraction, a greater ability to
298 recruit high-threshold type II motor units, and greater muscle activation rates (10).

299 Pennation angle in the GM showed a moderate, significant increase between pre- and
300 post-PHV, and a small, significant increase between circa- to post-PHV. The circa- to post-
301 PHV changes were larger than the typical error (CV%), and can be considered as meaningful
302 changes; however, the change from pre- to circa-PHV was only greater than the smallest-

303 worthwhile change (SWC) and not larger than the typical error, so should be viewed with
304 caution. These changes suggest that larger changes in pennation angle occur following PHV,
305 which may be explained by the nature of muscle architecture adaptation. The current study
306 found significant, small relationships between GM muscle thickness and pennation angle in
307 the whole cohort, as well as in the pre- and post-PHV groups. A greater muscle thickness would
308 necessitate a larger pennation angle, and therefore pennation angle increases may happen in
309 response to a muscle increasing in size (7). This may explain the significant increases in GM
310 muscle thickness between pre- to circa-PHV and then the subsequent increase in GM pennation
311 angle between circa- and post-PHV, where changes in muscle size manifest prior to alterations
312 in pennation angle. Comparable results between younger children have been reported in
313 previous literature, where pennation angle has been shown to be similar between children aged
314 between 5- 12 years (2). The current study found significantly greater GM pennation angle in
315 the post-PHV than in either the pre- or circa-PHV groups. The lack of difference between the
316 pre- and circa-PHV group suggest that GM pennation angle occurs later in maturation,
317 potentially following the preceding growth in muscle thickness. The larger pennation angle as
318 a result of maturation would likely improve the force-generating capabilities of a muscle (21),
319 through an increase in PCSA and muscle gearing (36), which would ultimately increase
320 explosive-type exercise commonly reported throughout maturation (22, 25, 35).

321 Muscle thickness in the VL significantly increased from pre- to circa-PHV and circa-
322 to post-PHV, with between-group differences exceeding the typical error (CV%). This
323 continuous increase in VL muscle thickness throughout maturation coincides with the
324 significant increase in body mass reported between the three maturity groups, again suggesting
325 the importance of mechanical loading on muscle growth. Interestingly, the increases in muscle
326 thickness of the VL across the different maturity groups differ to the growth pattern of the GM,
327 where changes between circa- to post-PHV were not significant. More growth occurs in the

328 femur compared to the tibia during childhood and adolescence (13), where the tibia may slow
329 in growth around the time of PHV, and the femur continues to grow further into adolescence.
330 Considering that growth in skeletal structures provides a stimulus for adaptation of muscle
331 tissue (37), the extended growth typically seen in the femur may explain the increases in VL
332 muscle thickness between circa- and post-PHV that are not seen in the GM. Similar increases
333 in muscle size for the VL have been reported between children and adults (20, 30), but these
334 findings do not offer insights into the complex and fluctuating process of maturation.

335 Pennation angle and fascicle length of the VL increased significantly between pre- to
336 post-PHV, and while all were above the SWC, only the change in VL fascicle length was above
337 the typical error. Similar findings related to fascicle length have been reported in previous
338 literature, whereby men were shown to have longer VL fascicles than boys (30). However, in
339 terms of VL pennation angle, findings from the current study differ to previous research, which
340 reported that pennation angle of the VL remained relatively stable between boys aged 11 years,
341 to 14 years and into adulthood (17), and that boys of approximately 9 years of age have similar
342 VL fascicle lengths to adults (30). The discrepancy in results between the current study and
343 previous research may be due to smaller sample sizes in the previous research. Intuitively,
344 greater increases in muscle thickness compared to pennation angle would require an increase
345 in fascicle length. This concept is supported by the current study, where a large negative
346 relationship was observed between pennation angle and fascicle length in both muscles.
347 Therefore, it can be assumed from this study that the increases in VL thickness are greater than
348 pennation angle, resulting in increased VL fascicle length. However, it can then be assumed
349 that the increase in thickness and pennation angle are similar in the GM, resulting in no
350 difference in fascicle length between the three groups.

351 The cumulative findings of the current study indicate that maturation may trigger
352 architectural adaptations within the GM and VL muscles that are likely to facilitate greater

353 force production and rate-of-force-development. Considering that muscle size is a major
354 predictor of maximum strength and power in children (34), the increases in muscle size with
355 maturation could be a major factor contributing to the improved capacity to produce force as
356 children transition through adolescence. Furthermore, considering that the VL muscle plays a
357 major role in sprinting and jumping tasks (8), the increase in the thickness of this muscle may
358 be a key factor in the improvement in the physical performance measures reported during
359 childhood and adolescence (22, 25, 35). The larger pennation angle demonstrated by the more
360 mature participants would allow the muscle to produce greater force, as a larger pennation
361 angle will increase the physiological cross-sectional area, resulting in a greater number of
362 contractile elements attaching to the aponeurosis or tendon for a greater force transfer (15).
363 The increase in pennation would also allow a muscle to take advantage of the “*gearing*” effect
364 during movement (36), which permits that muscle fascicles do not need to shorten to the same
365 extent as the overall muscle, permitting slower fascicle velocities in relation to whole muscle
366 velocities (36). This enables the fascicles to operate on a more optimal region of the force–
367 velocity curve and work at a favourable region of the force– length curve over a longer period,
368 maximising the force that the muscle can develop, without impacting on the capacity for rapid
369 movement production. Finally, the increased fascicle length due to the maturation process
370 would result in a greater muscle shortening velocity (21). The longer fascicles seen in the more
371 mature subjects would have a greater ability to produce force at higher velocities and over
372 larger length ranges, as more sarcomeres in series results in greater cumulative length change
373 of a fascicle within a given time. The increased number of sarcomeres in series may also result
374 in each individual sarcomere operating at a lower relative velocity, meaning greater force can
375 be produced by each fascicle (7).

376 To our knowledge, this is also the first report on the between-image and within-image
377 reliability of GM and VL architectural properties attained from ultrasound images recorded at

378 rest in pre- and post-PHV groups. Data indicated that the muscle architecture variables could
379 be reliably digitised at both within-image and between-image levels, with large to nearly
380 perfect ICC and CV values below the acceptance threshold (<10%). While reliability data on
381 ultrasonography-derived measures of muscle architecture remain scarce in youth populations,
382 when compared to results from a cohort of strength trained males (24), data from the current
383 study showed that the reliability of the digitising process both within- and between-images was
384 more varied in the pre-PHV cohort, and similar in the post-PHV cohort. The increased
385 variability in the pre-PHV cohort compared with older populations may be due to a larger fat
386 mass seen in this population (23). Adipose tissue has less degrees of reflection than muscle due
387 to different acoustic impedance (32). The greater fat mass seen in the younger children may
388 weaken the generated reflection and reduce the quality of the ultrasound image (32), causing
389 more variance in the digitisation and determination of muscle architectural variables.

390 The current study has made a novel contribution to the developmental literature
391 surrounding paediatric muscle architecture. However, it is important to consider certain
392 limitations within the study. Considering the dimensions of the linear probe being used, it was
393 necessary to estimate fascicle length from measures of muscle thickness and pennation angle
394 using a previously published equation (6). The model assumes that fascicles are straight and
395 does not account for fascicle curvature, however this equation has been used in previous
396 studies (6) and has been shown to result in an error of only approximately 3% for relaxed
397 muscles with short fascicles (4). Additionally, fascicle length of the GM and VL was made
398 relative to leg length in the current study. However, for more accurate relative measures, the
399 GM fascicle length would need to be made relative to the shank length, and VL fascicle length
400 made relative to thigh length. The current study used a cross-sectional research design;
401 however, future research is now required to validate these findings by longitudinally measuring
402 changes in muscle architecture characteristics in youth of varying maturity levels. Furthermore,

403 while this study has gone some way into highlighting the differences in muscle architecture
404 during maturity, the influence that this has on physical performance in tasks such as sprinting
405 and jumping remains unknown.

406

407 CONCLUSION

408 The current study showed that all muscle architecture variables showed significant
409 small to large increases from pre- to post-PHV, with the exception of GM fascicle length. These
410 findings indicate that maturation underlies changes in muscle morphology, and that maturation
411 may trigger architectural adaptations within the GM and VL muscles that are likely to facilitate
412 greater force production and rate-of-force-development. This study establishes maturity-
413 related changes in muscle architecture variables that provides researchers and practitioners
414 with reference data that can be used to differentiate between training induced adaptations
415 versus those realised as a consequence of growth and maturation. For example, the data showed
416 that an increase in 0.3 cm was observed in VL muscle thickness between pre- to circa-PHV;
417 therefore, any adaptations would need to exceed this value to confirm changes were not
418 attributable solely to the maturational process.

419

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