

1 Pediatric Exercise Science - Special Issue - Gaps in our Knowledge

2 **Musculoskeletal proportionality, biomechanical considerations and their contribution to**  
3 **movement in adults and children**

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5  
6 **Abstract**

7 The musculoskeletal system grows greatly throughout maturation. When trying to explain differences  
8 in strength, power and movement patterns between adults and children many pediatric exercise  
9 scientists will assume that this growth is proportional in all dimensions and structures. This article  
10 examines the evidence underpinning these assumptions, and considers how changes in fascicle,  
11 muscle, tendon and joint proportions may contribute to maturation-induced changes in physical  
12 performance. There are only a small number of studies to draw upon, but they consistently indicate  
13 that 1) growth changes the functional design of muscles, so that they become better at producing  
14 large forces at slow speeds but less able to achieve large length changes or high velocities; 2) the  
15 skeleton appears to grow somewhat proportionally prior to puberty, but this changes throughout  
16 adolescence, meaning the moment arm about which the muscle acts does not remain proportional to  
17 muscle length or the external moment arm about which joint work acts on the external world. In  
18 combination these results show that external measures of whole body or joint performance do not  
19 reflect the actual internal muscle function similarly in children and adults. Since our purpose should  
20 be to explain and not just describe maturation-induced changes in performance, greater efforts are  
21 needed to understand the internal "engine" driving our movement. This necessitates more detailed,  
22 longitudinal and dynamically loaded studies of the structure and function of the muscles and their  
23 interaction with the skeleton throughout maturation.

24

25 **What we know**

26

27 We know that children are not small scale adults in many ways. In movement and exercise the  
28 changing body dimensions result not only in maturation-induced improvements in performance  
29 during powerful, anaerobic tasks (e.g., 23, 24) but also changes in movement patterns. This is apparent  
30 during challenging locomotor tasks (4), drop jumping (10, 11) and cycling (7), for example. Complex  
31 structural and neural interactions, which develop with maturation and learning, have been reported  
32 to contribute to optimise performance, and will underpin part of these movement differences (these  
33 are reviewed by Blazeovich *et al.*, 3).

34

35 In less complex actions, such as isolated joint efforts, maximum strength and power is known to  
36 increase with maturation (e.g., 18, 20) and adult-child differences are particularly apparent at higher  
37 contraction velocities (e.g., 1, 6, 15). These may be explained by maturation-related differences in  
38 recruitment of larger motor units (5). Alternatively, it has been postulated that increases in the rate  
39 of force development (28) or tendon stiffness (9, 16, 27) would allow adults to reach their peak  
40 moment earlier in the movement and closer to the optimum joint angle than children. The implication  
41 here is that, during a rapid dynamic contraction children may not be able to generate maximum force  
42 over the same portion of the muscle's force-length curve as adults do, and may not utilise the joint  
43 angle associated with optimum muscle length maximally. This would mean that the externally  
44 measured performance does not reflect the actual internal muscle capabilities, and would present as  
45 a lower strength in children at the highest contraction velocities.

46

47 Many studies do not consider such factors as affecting their measurements, but it should be  
48 remembered that muscles are the "engine" that drive our joint and whole body movements. While

49 measured differences in performance of adults and children are important to quantify, without a  
50 detailed understanding of the internal muscle behaviour and function it is not possible to fully explain  
51 the external differences; and that ultimately should be the purpose of fundamental biological studies  
52 of development.

53

54 Some studies make simple assumptions about the proportionality of body dimensions when  
55 interpreting performance measures. A good example of this was the normalisation of joint moment  
56 to an estimate of thigh volume; with the justification that volume is the product of cross-sectional  
57 area, which is proportional to force, and length which is of the same dimension as moment arm length  
58 (moment=force x moment arm) (8, 6). Alternatively, others attempt to determine muscle and joint  
59 function using simulation models, but these commonly rely on generic musculoskeletal models that  
60 are rescaled from adult size to a proportionally smaller “child size”; errors associated with generic  
61 rescaling have been reported previously (21). These approaches are appealing, partly because the data  
62 needed for more appropriately scaled models may be lacking, but also because they are simple.  
63 However the assumptions are not robust, since scaling is not directly proportional to stature or mass,  
64 often not explained by some relevant biological principle (31), and can induce non-trivial errors. It is  
65 imperative that paediatric exercise scientists better understand the proportionality of the  
66 musculoskeletal system so that performance and movement changes can be better explained.

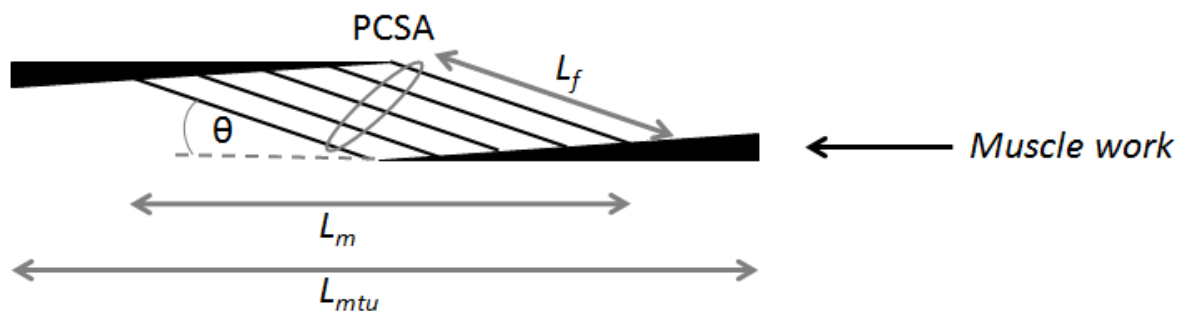
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68 Numerous studies and several excellent reviews exist that describe the interactions between muscle  
69 architecture, tendon properties and joint moment (lever) arms, and how changes in the  
70 proportionality between these determine the outcome of muscle contraction (e.g. 12). It is not the  
71 purpose of this discussion to duplicate those, but for completeness a summary of the major factors  
72 will follow.

73

74 The primary skeletal muscles contributing to locomotion are pennate (see figure 1 for a representation  
75 of muscle and fascicle architecture), and as such can modify their fascicular architecture to achieve an  
76 optimal muscle function “design”. Within a given muscle mass, a highly pennate muscle (i.e, steep  
77 pennation angle) has a large physiological cross-sectional area and is better suited to producing large  
78 forces, whilst a shallower pennation angle increases fascicle length and allows high contraction  
79 velocities.

80



81

82 Figure 1. A planimetric representation of muscle architecture in a pennate muscle ( $\theta$ : pennation  
83 angle). Functionally important length quantities include that of the muscle tendon unit ( $L_{mtu}$ ), muscle  
84 ( $L_m$ ), tendon (the difference between  $L_{mtu}$  and  $L_m$ ) and the fascicles ( $L_f$ ). Force producing capacity is  
85 proportional to the physiological cross-sectional area (PCSA), measured as the summed cross-  
86 sectional area of all fascicles.

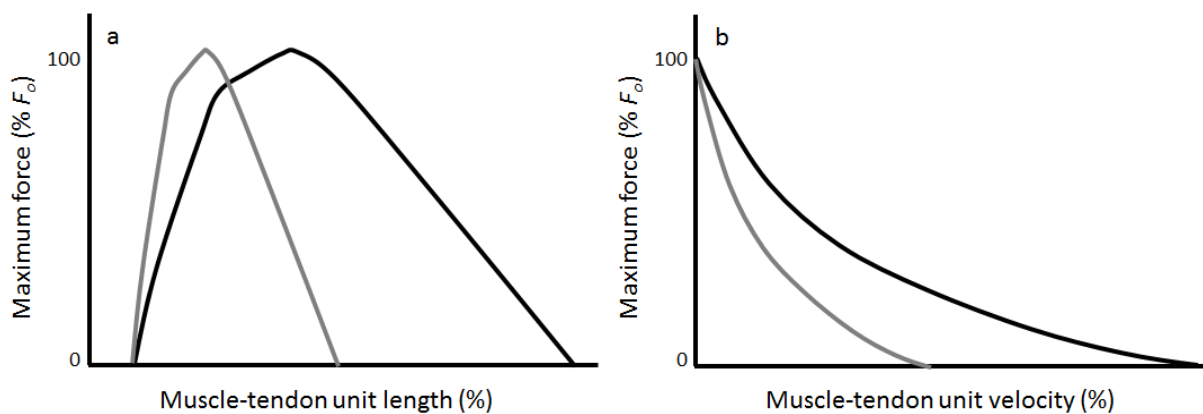
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88 Fascicle length is also important because it determines the range of motion over which muscle force  
89 can be produced, i.e. the functional range of motion. Muscles with longer fascicles are able to produce  
90 forces closer to their maximum across a wider portion of their range of motion than muscles with  
91 shorter fascicles. Since relative shortening is less in muscles with long fascicles, relative contractile  
92 velocity is lower and according to the force-velocity relationship this would allow the muscle to

93 produce a greater force at any given muscle velocity. To scale fascicle lengths and excursions between  
94 individuals of differing/changing sizes (i.e., adults and children), fascicle length is normalised as the  
95 fascicle:muscle-tendon or simply fascicle:tendon length ratio (see figure 2 or (12) for further  
96 explanation).

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98



99

100 Figure 2. Representations of the (a) force-length and (b) force velocity curves for two muscle-tendon  
101 units that are identical apart from one has a large (—) and the other small (—) fascicle:tendon  
102 length ratio. Maximum force is expressed as a percentage of isometric force at optimum length.  
103 Muscle-tendon length and velocity are expressed relative to slack length.

104

105

106 The amount of muscle-tendon unit shortening during a joint rotation depends on the moment arm  
107 length of the muscle about the joint (defined as the perpendicular distance between the joint centre  
108 to the line of action of the muscle-tendon force). Longer moment arms are beneficial for transferring  
109 force to moments, but necessitate a longer muscle-tendon length change to achieve a given joint  
110 rotation. In the case of adult-child comparisons, the moment arm length also requires consideration

111 of the proportions of the muscle-tendon unit and fascicles that will be shortened by joint rotation.  
112 This is accounted for by the moment arm:fascicle length ratio. Whereby, a smaller ratio will mean less  
113 fascicle shortening for a given joint rotation and the same positive effects for a wide functional range  
114 of motion and muscle force at high velocities outlined above.

115

116 Once work is created about the joint, the distal segment must then act against external objects (e.g.  
117 the ground or a mass being displaced) to achieve the desired task (e.g., running, jumping or throwing).  
118 The outcome of this depends on the length of the external moment arm (the perpendicular distance  
119 between the joint centre to the line of action of the external reaction force, e.g. ground reaction  
120 force). External moment arm can be manipulated by alterations in movement technique, but also  
121 depends on the anatomical dimensions of the skeletal segment(s). In some cases the external moment  
122 arm length would be equal, or certainly proportional, to the distal skeletal segment length, and  
123 therefore valid comparison of externally measured force (as opposed to moment) and linear velocity  
124 between individuals relies on equal proportionality of internal moment arms to skeletal dimensions;  
125 the anatomical internal:external moment arm ratio, often known as the joint mechanical advantage.  
126 Given that the growth plate is located at the end of the long bones, between the joint and attachment  
127 of the tendon, internal moment arm length (from joint centre to the line of action of the muscle-  
128 tendon force) is expected to increase when the bone lengthens during maturation. However, there is  
129 no certainty that the bone lengthens proportionally along its shaft. Consequently the  
130 internal:external moment arm ratio, and so joint mechanical advantage, may not remain constant  
131 with maturation.

132

133 During isometric contractions, the joint moment is equal to the product of muscle force (proportional  
134 to physiological cross-sectional area) and the muscle moment arm length. This means that at any  
135 common joint angle or muscle length, even if the muscle of an adult were not able to produce more

136 force than a child's, by virtue of having a longer moment arm length, their apparent strength would  
137 be greater. The addition of sarcomeres in series to increase fascicle length during growth would not  
138 increase isometric muscle force. However, the longer fascicle length would reduce relative excursion  
139 during joint rotation and thereby the position on the force-length relationship that is utilised at any  
140 given joint angle. Moreover, any differences in the profile of the moment arm-joint angle relationship  
141 between individuals might further confound comparisons of strength at single joint angles. Therefore,  
142 care must be taken during strength testing to ensure all participants are tested at joint angles that  
143 correspond similarly to the optimum angle. This might necessitate differing joint angles across groups,  
144 ages, or individuals, but this in itself is an important functional outcome that should be reported. This  
145 discussion is primarily concerned with movement characteristics, and isometric strength will not be  
146 specifically addressed further, although the joint moment-angle profile is inherently implicated in  
147 discussion of muscle length changes.

148

149 It is clear that there are many anatomical characteristics and multiple structures that interact to  
150 determine the outcome of muscle contraction. When the relative proportions of those structures are  
151 not equal across individuals, external measures of performance cannot be assumed to reflect internal  
152 muscle function similarly. Alternatively, if taking a forward dynamics approach (i.e., predicting the  
153 external movement outcome based on the internal musculoskeletal characteristics), identical muscle  
154 function would not result in similar body movements. Thus, variations in musculoskeletal  
155 proportionality may contribute to the differences seen between adults and children in performance  
156 and neural drive characteristics.

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158

159

160 **What are the gaps?**

161 This section describes what is known about the pertinent musculoskeletal proportions in children and  
162 the proportionality between children and adults, the limitations of our current understanding, and  
163 what is not known. The discussion focuses on the knee extensors and the gastrocnemius as the most  
164 common muscles studied and important locomotor muscles. Data on upper limb muscle strength  
165 relative to measures of size have been reported (6), but beyond this our knowledge about the growth  
166 of upper limb musculoskeletal structure is lacking. This in itself is an important gap in our knowledge.

167

168 The most detailed analysis of quadriceps muscle architecture in children and adults was undertaken  
169 by O'Brien *et al.* (17). In this study muscle volume and length were quantified from magnetic  
170 resonance imaging and fascicle architecture was measured from ultrasound images at multiple sites  
171 along the length and across each of the four heads. It was reported that muscles and fascicles of  
172 children were smaller and shorter than in adults, but pennation angle did not differ. Despite the similar  
173 pennation angle across ages and sexes, a different functional design was still identified, with greater  
174 differences in physiological cross-sectional area (men 2.1 times that in boys) than fascicle length (men  
175 1.3 times that in boys); indicating a shift towards a muscle better suited to force production in adults  
176 compared to children. *Please note, this is not an attempt at allometric scaling of muscle growth, but*  
177 *a reflection of changing functional design that occurs during growth.*

178

179 Although differences in fascicle lengths were detected, they were proportional to total muscle-tendon  
180 length in all four quadriceps heads. This indicates proportionality in the growth of muscle length and  
181 would lead to similar relative length changes in the fascicles and sarcomeres during a shortening of  
182 the muscle-tendon unit, and thus comparable excursion across the force-length relationship. This

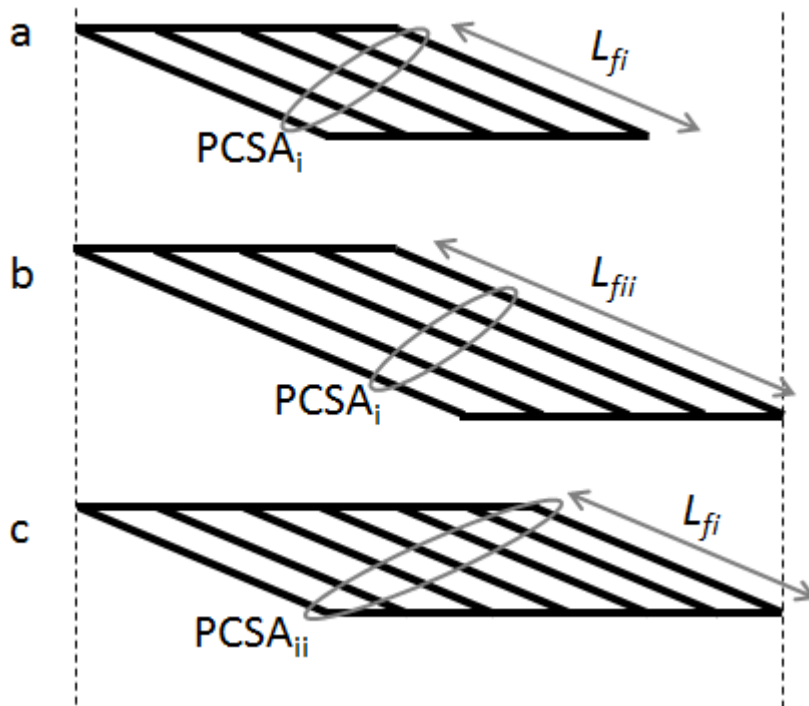


183 excludes the possibility that differences in movement patterns of adults and children can be explained  
184 by fascicle behaviour in relation to behaviour of the quadriceps muscle-tendon unit.

185

186 In the lateral gastrocnemius, fascicle length has been reported to be shorter in boys than men, but an  
187 equal proportion of muscle length in both ( $\sim 0.36$ ) (13). In contrast, an analysis of a 3D reconstruction  
188 of ultrasound images (30) found that absolute fascicle length in the medial gastrocnemius was not  
189 different between a group of boys and young men ( $\sim 6$  cm at 0 Nm passive joint moment) and did not  
190 correlate with age ( $r=0.17$ ). Instead, the greater muscle-tendon length necessitated by skeletal growth  
191 was achieved by increasing physiological cross-sectional area (in a pennate muscle the physiological  
192 cross-sectional area contributes to muscle length; see figure 3). These results must be interpreted with  
193 care given the modest sample number and large inter-subject variability resulting from the wide age  
194 range. The combination of which may be the reason that the fascicle:tibia (which determines muscle-  
195 tendon unit) length ratio did not change with age, contradicting the former observation. However, the  
196 lack of growth of medial gastrocnemius fascicle length is supported by a previous animal study from  
197 that group. If fascicle length relative to muscle-tendon length is smaller in adults than in children, it  
198 would be expected that fascicles of adults undergo a greater excursion for a given muscle-tendon unit  
199 length change than in children. The consequence would be that, the decline in muscle force during  
200 contraction at lengths away from optimum, or at increasing velocity (see figure 2) will be a greater in  
201 adults than in children. This would have significant implications for movement in dynamic situations,  
202 and result in adults being less forceful during high velocity contractions. Although the plantarflexor  
203 power-velocity profile of adults and children has not been established previously, this is not consistent  
204 with most previous observations of performance. Thus, intermediate factors must contribute; these  
205 may be structural, as are discussed here, or neural. Clearly additional work is required in this area to  
206 clarify our understanding.

207



208

209 Figure 3. An illustration of how a pennate muscle (a) can increase its overall length by either (b)  
 210 increasing the length of the fascicles ( $L_{fii} > L_{fi}$ ) or (c) by increasing physiological cross-sectional area  
 211 ( $PCSA_{ii} > PCSA_i$ ) but not changing fascicle length ( $L_{fi}$ ). This is the mechanism proposed by Weide *et al.*  
 212 (30) for growth of the medial gastrocnemius length.

213

214 An important factor that influences muscle-tendon shortening is the length of the muscle's moment  
 215 arm; specifically, the proportionality of the moment arm:fascicle length ratio. This ratio has not been  
 216 reported previously, but combining the existing moment arm length data (15) with fascicle lengths in  
 217 the same children (17), the moment arm:fascicle length ratio in the vastus lateralis was (mean±SD)  
 218  $0.53 \pm 0.04$  and  $0.52 \pm 0.06$  for men and women vs.  $0.55 \pm 0.07$  and  $0.57 \pm 0.05$  for boys and girls,  
 219 respectively, with a significant adults-children difference ( $p=0.03$ , 95% CI =  $-0.074, -0.004$ ). When  
 220 combined with comparable fascicle:tendon length ratios, this indicates that a given knee joint rotation  
 221 would result in a greater relative fascicle shortening in children than in adults. This would make  
 222 children less able to produce high velocity joint rotations. In terms of adults' function, the smaller

223 moment arm:fascicle length ratio would help to increase maximum joint velocity, and may go some  
224 way to offset the change in functional design towards more force production. It must be recognised  
225 however that this is based on the length of the patellar tendon moment arm and not the effective  
226 moment arm length of the entire knee extensor mechanism, which includes the patella and the  
227 quadriceps tendon. This limitation should be rectified in studies specifically designed to address this  
228 issue.

229

230 At the ankle, Morse *et al.* (13) presented data on lateral gastrocnemius fascicle length and on Achilles  
231 tendon moment arm length, the ratio of the reported group means is virtually equal in men and boys  
232 ( $\sim 0.83$  using resting fascicle length). This data should be interpreted with the consideration that the  
233 fascicle lengths contradict those reported recently (30), and that although Waugh *et al.* (26) found a  
234 positive relationship between Achilles tendon moment arm and leg length (incorporating tibia length  
235 which determines muscle-tendon length) in a group of children, they were associated with weak  $R^2$ -  
236 values and included only pre-pubertal children, so scaling to adults is not clear. Thus, there is  
237 contradicting and scant information about how moment arm length impacts fascicle function in the  
238 gastrocnemius muscles of children.

239

240 The final anatomical proportion to be discussed is the joint mechanical advantage (internal:external  
241 moment arm length ratio). For the quadriceps, anatomically this ratio would be relative to tibia length.  
242 In children, moment arm of the patellar tendon has been found to be proportional to many  
243 anthropometric dimensions (e.g. leg length, knee breadth) including tibia length (15). In adults, fewer  
244 significant relationships were found, all with weak correlations, and tibia length was not correlated  
245 with patellar tendon moment arm. We can conclude that in pre-pubertal children mechanical  
246 advantage at the knee is constant and external measures of force and linear velocity taken at the end

247 of the tibia or foot faithfully reflect internal behaviour. This is not the case in adults, for whom the  
248 skeletal proportions vary greatly, and internal performance is not well reflected by external measures.

249

250 Waugh et al. (26) scaled Achilles moment arm length to foot length and, similarly to their finding on  
251 leg length, reported a positive relationship but a weak  $R^2$ -value amongst children. It is not known how  
252 this may change with maturation, and conclusions about the effect of internal:external moment arm  
253 lengths on movement at the ankle cannot be drawn. At both the knee and ankle it appears that the  
254 proportionality of anatomical leverage changes during growth. However, little is known about how  
255 the anatomical external moment arm of the lower leg or foot is utilised during movement, and how  
256 they impact the functional external moment arm of, for example, the ground reaction force, which  
257 often does not equal the anatomical one.

258

259 All of the studies discussed here made anatomical measurements in passive conditions and this  
260 information has been used to make inferences about function during dynamic, loaded tasks based on  
261 our knowledge of musculoskeletal interactions. This neglects the fact that many of these dimensions  
262 change with loading; moment arms are also known to change when the joint is loaded (22), although  
263 this work has not been conducted in children; and the series elastic tissues within the muscle-tendon  
264 unit elongate non-linearly with increasing load, and cause the muscle to shorten. We know stiffness  
265 of both free tendon and the tendon-aponeurosis complex is lower in children than in adults (9, 16,  
266 27), but it is not known how these structures behave during dynamic actions with varying loads, often  
267 below maximal muscle force. In addition, if the muscle-tendon unit is to be modelled correctly, it is  
268 actually the slack muscle length (when passive force is 0N so muscle length is not changed by tension  
269 or compression) that is required as an input. Whilst some studies have made an effort to approximate  
270 this by making measurements with the muscle in its shortest possible position it cannot be certain,  
271 and this is not the same for all studies.

272

273 Scrutinising the body of literature available, it is apparent that we have very few pieces of the jigsaw  
274 and the pieces we do have are rarely made on samples large enough to truly quantify whole  
275 population based characteristics and variability, and the data they generate are only applicable in few  
276 conditions. In comparison to the vast body of literature that exists describing performance and  
277 movement differences between adults and children, it is difficult to make firm conclusions about the  
278 internal behaviour and function of the muscles and their fascicles during a range of dynamic tasks. We  
279 can be fairly certain that muscle-tendon behaviour in the quadriceps and gastrocnemius is different  
280 between adults and children, but beyond that their influence in explaining maturation-related changes  
281 in whole body performance and function remains inexact.

282

283 The only study to date that has quantified and compared muscle behaviour in adults and children  
284 during a functionally relevant dynamic task, found greater relative fascicle excursions in the medial  
285 gastrocnemius in children than in adults, but differences in velocity were not detected (29). This study  
286 was presented as a poster at the 2015 International Society of Biomechanics, and a detailed protocol  
287 and data set are required for complete understanding; we look forward to seeing the full paper in due  
288 course.

289

290 There is early evidence indicating that the proportionality of growth is different during childhood and  
291 adolescence. Prior to puberty there is high correlation between many anthropometric dimensions, of  
292 the body and lower limb, including moment arm length of the patellar tendon (15). This is supported  
293 by observations that growth of the medial gastrocnemius up to the age of 12 years, is equally  
294 attributable to increases in fascicle length and physiological cross-sectional area (2). In combination,  
295 these findings suggest a proportionality in growth of the musculoskeletal system prior to puberty.

296 However, the growth of adolescence appears not to be proportional in all dimensions and introduces  
297 greater inter-individual variability, resulting in changed muscle functional design (17, 30) and a lack of  
298 correlation between skeletal dimensions (15) by adulthood. Although these cross-sectional studies  
299 show us the outcome of growth, they do not inform us about the timing, process or rate by which  
300 proportionality appears to change during maturation.

301

302

### 303 **How can we fill these gaps?**

304 In most biomechanical modelling applications, experimenters choose to use generic scaled models  
305 based on existing adult anatomical data sets, and use some scaling factor for all structures and  
306 dimensions. This approach is often accepted as it is argued to be the only pragmatic solution and, very  
307 appealingly, it is simple. As long as this approach is considered acceptable in cases where the  
308 populations for comparison vary greatly, less emphasis will be placed on establishing the true  
309 anatomical characteristics of the population of interest; in our case, children.

310

311 We first need more studies of musculoskeletal proportions and their interactions in adults and  
312 children. Magnetic resonance imaging and ultrasound, particularly the increasingly available 3D  
313 ultrasound reconstructions, should be used where possible to obtain the greatest quantity and highest  
314 quality of data. These studies must make efforts to control factors known to influence the  
315 measurements, such as passive joint torque or muscle-tendon force and joint angle (30), and it is  
316 imperative to make measurements that are most suitable to use in the modelling applications.  
317 Specifically, investigators should seek to quantify the important functional ratios of fascicle:tendon,  
318 moment arm:fascicle and internal:external moment arms in a large group of children, and preferably  
319 follow them longitudinally. This approach would tell us about the nature of human growth with

320 maturation and provide a database of typical development. This will not only have applications in  
321 human movement sciences, but also provide reference values for clinical investigations.

322

323 Second, studies that quantify the excursions and velocity of the fascicles during movement should be  
324 undertaken across a wide range of athletic tasks. The measurements presented at the International  
325 Society of Biomechanics (29) are a useful start and show that we are able to conduct such experiments  
326 in children, but more is required if we are to further our understanding. Wakeling *et al.* (25) have  
327 shown that during cycling the activation characteristics and power output of adults are related to  
328 fascicle behaviour during the task. Activation characteristics during cycling are also known to differ  
329 between adults and children (19), and we should utilise these techniques to help us identify or  
330 eliminate possible explanations and progress closer to the true cause(s). This work also needs to try  
331 and align our understanding of predicted muscle function, based on anatomical characteristics, and  
332 the observed behaviour. The need for this will hopefully be recognised and included in the published  
333 manuscript from Waugh *et al.*, which should help us better understand the effects of possibly similar  
334 fascicle lengths in longer muscle-tendon units in adults compared to children (30).

335

336 Once the anatomical database exists, modelling studies can become an important next step.  
337 Combined with motion data, anatomical data can be used to simulate muscle behaviour and function  
338 during a range of athletic actions, and validated against the observed muscle-tendon behaviour and  
339 measured performance outcomes. At that point the contributions of changing musculoskeletal  
340 proportions, causing altered internal muscle-tendon behaviour can be used to explain the externally  
341 observed differences. This is not a short, nor easy path. It requires the contributions of a range of  
342 integrative physiologists, biomechanists and engineers, but further observations of external  
343 movement alone will do little to make large strides forwards in this area. If we really want to

344 understand the mechanisms that explain the changes in performance and movement that we see with  
345 maturation, we must study the function of the inner “engine” driving the movement.

346

347



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