Pediatric Exercise Science - Special Issue - Gaps in our Knowledge

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

Thomas D. O'Brien

Abstract

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

What we know

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

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

Many studies do not consider such factors as affecting their measurements, but it should be remembered that muscles are the "engine" that drive our joint and whole body movements. While measured differences in performance of adults and children are important to quantify, without a detailed understanding of the internal muscle behaviour and function it is not possible to fully explain the external differences; and that ultimately should be the purpose of fundamental biological studies of development.

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

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

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

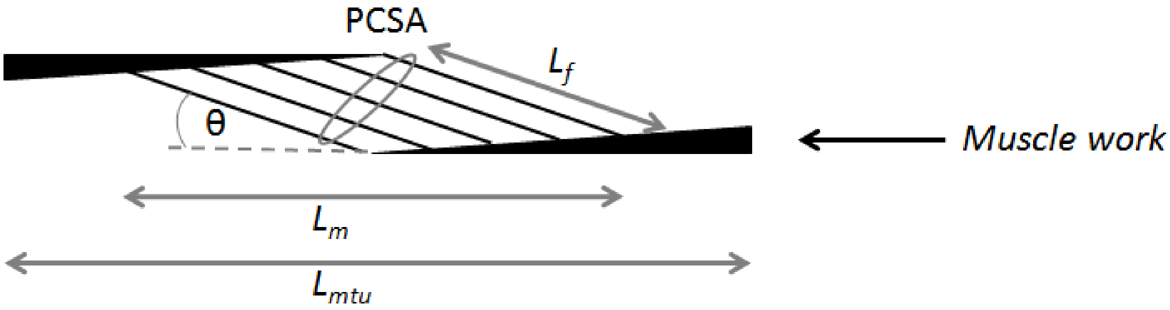

Figure 1. A planimetric representation of muscle architecture in a pennate muscle (θ: pennation angle). Functionally important length quantities include that of the muscle tendon unit (L_{mtu}), muscle (L_m), tendon (the difference between L_{mtu} and L_m) and the fascicles (L_f). Force producing capacity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

Fascicle length is also important because it determines the range of motion over which muscle force can be produced, i.e. the functional range of motion. Muscles with longer fascicles are able to produce forces closer to their maximum across a wider portion of their range of motion than muscles with shorter fascicles. Since relative shortening is less in muscles with long fascicles, relative contractile velocity is lower and according to the force-velocity relationship this would allow the muscle to produce a greater force at any given muscle velocity. To scale fascicle lengths and excursions between individuals of differing/changing sizes (i.e., adults and children), fascicle length is normalised as the fascicle:muscle-tendon or simply fascicle:tendon length ratio (see figure 2 or (12) for further explanation).

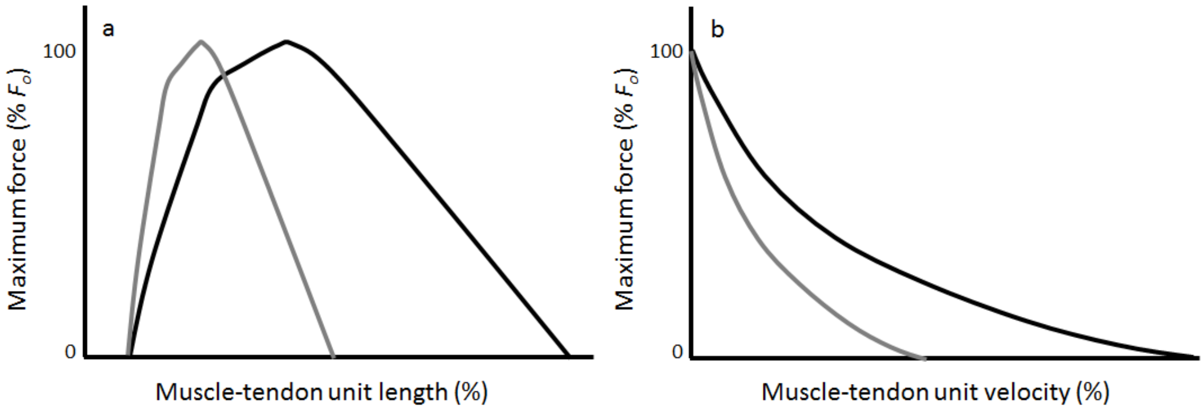

Figure 2. Representations of the (a) force-length and (b) force velocity curves for two muscle-tendon units that are identical apart from one has a large (▬) and the other small (▬) fascicle:tendon length ratio. Maximum force is expressed as a percentage of isometric force at optimum length. Muscle-tendon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

The amount of muscle-tendon unit shortening during a joint rotation depends on the moment arm length of the muscle about the joint (defined as the perpendicular distance between the joint centre to the line of action of the muscle-tendon force). Longer moment arms are beneficial for transferring force to moments, but necessitate a longer muscle-tendon length change to achieve a given joint rotation. In the case of adult-child comparisons, the moment arm length also requires consideration of the proportions of the muscle-tendon unit and fascicles that will be shortened by joint rotation. This is accounted for by the moment arm:fascicle length ratio. Whereby, a smaller ratio will mean less fascicle shortening for a given joint rotation and the same positive effects for a wide functional range of motion and muscle force at high velocities outlined above.

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

During isometric contractions, the joint moment is equal to the product of muscle force (proportional to physiological cross-sectional area) and the muscle moment arm length. This means that at any common joint angle or muscle length, even if the muscle of an adult were not able to produce more force than a child’s, by virtue of having a longer moment arm length, their apparent strength would be greater. The addition of sarcomeres in series to increase fascicle length during growth would not increase isometric muscle force. However, the longer fascicle length would reduce relative excursion during joint rotation and thereby the position on the force-length relationship that is utilised at any given joint angle. Moreover, any differences in the profile of the moment arm-joint angle relationship between individuals might further confound comparisons of strength at single joint angles. Therefore, care must be taken during strength testing to ensure all participants are tested at joint angles that correspond similarly to the optimum angle. This might necessitate differing joint angles across groups, ages, or individuals, but this in itself is an important functional outcome that should be reported. This discussion is primarily concerned with movement characteristics, and isometric strength will not be specifically addressed further, although the joint moment-angle profile is inherently implicated in discussion of muscle length changes.

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

What are the gaps?

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

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

Although differences in fascicle lengths were detected, they were proportional to total muscle-tendon length in all four quadriceps heads. This indicates proportionality in the growth of muscle length and would lead to similar relative length changes in the fascicles and sarcomeres during a shortening of the muscle-tendon unit, and thus comparable excursion across the force-length relationship. This excludes the possibility that differences in movement patterns of adults and children can be explained by fascicle behaviour in relation to behaviour of the quadriceps muscle-tendon unit.

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

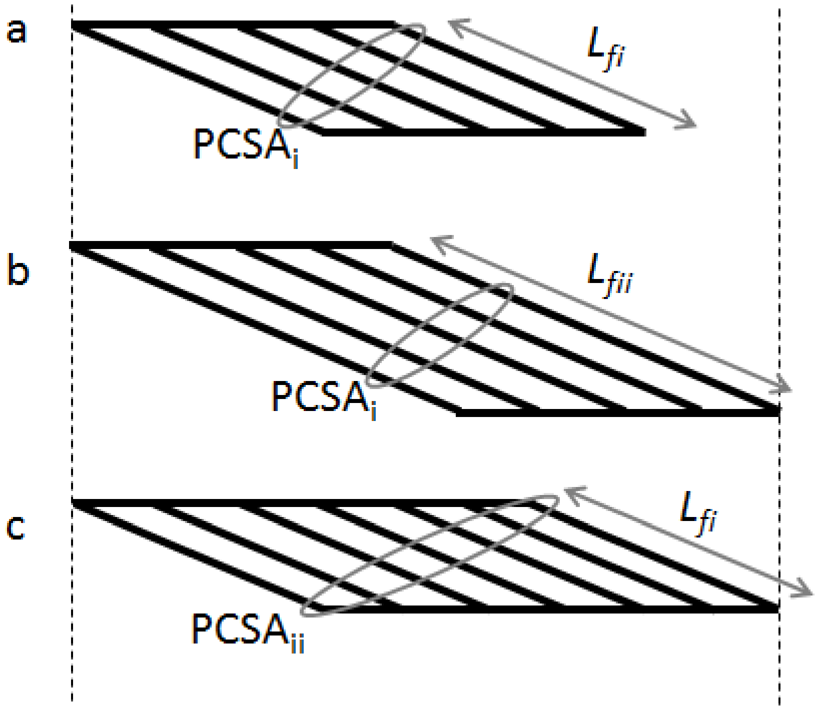

Figure 3. An illustration of how a pennate muscle (a) can increase its overall length by either (b) increasing the length of the fascicles ($L_{fii} > L_{fi}$) or (c) by increasing physiological cross-sectional area ($PCSA_{ii} > PCSA_i$) but not changing fascicle length (L_{fi}). This is the mechanism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

An important factor that influences muscle-tendon shortening is the length of the muscle's moment arm; specifically, the proportionality of the moment arm:fascicle length ratio. This ratio has not been reported previously, but combining the existing moment arm length data (15) with fascicle lengths in the same children (17), the moment arm:fascicle length ratio in the vastus lateralis was (mean±SD) 0.53±0.04 and 0.52±0.06 for men and women *vs*. 0.55±0.07 and 0.57±0.05 for boys and girls, respectively, with a significant adults-children difference ($p=0.03$, 95% CI = -0.074,-0.004). When combined with comparable fascicle:tendon length ratios, this indicates that a given knee joint rotation would result in a greater relative fascicle shortening in children than in adults. This would make children less able to produce high velocity joint rotations. In terms of adults' function, the smaller moment arm:fascicle length ratio would help to increase maximum joint velocity, and may go some way to offset the change in functional design towards more force production. It must be recognised however that this is based on the length of the patellar tendon moment arm and not the effective moment arm length of the entire knee extensor mechanism, which includes the patella and the quadriceps tendon. This limitation should be rectified in studies specifically designed to address this issue.

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

The final anatomical proportion to be discussed is the joint mechanical advantage (internal:external moment arm length ratio). For the quadriceps, anatomically this ratio would be relative to tibia length. In children, moment arm of the patellar tendon has been found to be proportional to many anthropometric dimensions (e.g. leg length, knee breadth) including tibia length (15). In adults, fewer significant relationships were found, all with weak correlations, and tibia length was not correlated with patellar tendon moment arm. We can conclude that in pre-pubertal children mechanical advantage at the knee is constant and external measures of force and linear velocity taken at the end of the tibia or foot faithfully reflect internal behaviour. This is not the case in adults, for whom the skeletal proportions vary greatly, and internal performance is not well reflected by external measures.

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

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

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

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

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

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

How can we fill these gaps?

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

We first need more studies of musculoskeletal proportions and their interactions in adults and children. Magnetic resonance imaging and ultrasound, particularly the increasingly available 3D ultrasound reconstructions, should be used where possible to obtain the greatest quantity and highest quality of data. These studies must make efforts to control factors known to influence the measurements, such as passive joint torque or muscle-tendon force and joint angle (30), and it is imperative to make measurements that are most suitable to use in the modelling applications. Specifically, investigators should seek to quantify the important functional ratios of fascicle:tendon, moment arm:fascicle and internal:external moment arms in a large group of children, and preferably follow them longitudinally. This approach would tell us about the nature of human growth with maturation and provide a database of typical development. This will not only have applications in human movement sciences, but also provide reference values for clinical investigations.

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

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

References

1. Asai H & Aoki J. Force development of dynamic and static contractions in children and adults. *Int J Sports Med.* 1996; 17(3), 170–4.

2. Benard MR, Harlaar J, Becher JG, Huijing PA & Jaspers RT. Effects of growth on geometry of gastrocnemius muscle in children: a three dimensional ultrasound analysis. *J Anat*. 2011; 219, 388–402.

3. Blazevich A, Waugh C & Korff T. Development of musculoskeletal stiffness; in *Paediatric Biomechanics and Motor Control; theory and application*, Ed. De Ste Croix & Korff. 2012; Routledge, Oxon, England.

4. Cesar GM & Sigward SM. Dynamic stability during running gait termination: Differences in strategies between children and adults to control forward momentum. *Hum Mov Sci*. 2015; 43, 138-45.

5. Dotan R, Mitchell C, Cohen R, Klentrou P, Gabriel D, Falk B (2012). Child-adult differences in muscle activation--a review. *Pediatr Exerc Sci*. 2015; 24, 2-21.

6. Kanehisa H, Abe T & Fukunaga T (2003). Growth trends of dynamic strength in adolescent boys. A 2-year follow-up survey. *J Sports Med Phys Fitness* 43, 459–464.

7. Korff T, Hunter EL & Martin JC (2009). Muscular and non-muscular contributions to maximum power cycling in children and adults: implications for developmental motor control. *J Exp Biol* 212, 599-603.

8. Kubo K, Kanehisa H, Kawakami Y, Fukanaga T (2001). Growth changes in the elastic properties of human tendon structures. *Int J Sports Med* 22, 138–143.

9. Kubo K, Teshima T, Hirose N, Tsunoda N (2014). Growth changes in morphological and mechanical properties of human patellar tendon in vivo. *J Appl Biomech* 30, 415-22.

10. Lazaridis S, Bassa E, Patikas D, Giakas G, Gollhofer A, Kotzamanidis C (2010). Neuromuscular differences between prepubescents boys and adult men during drop jump. *Eur J Appl Physiol* 110, 67–74.

11. Lazaridis S, Bassa E, Patikas D, Hatzikotoulas K, Lazaridis FK & Kotzamanidis C (2013).Biomechanical comparison in different jumping tasks between untrained boys and Men. *Pediatric Exercise Science* 25, 101-113

12. Lieber RL & Fridén J. Functional and clinical significance of skeletal muscle architecture. *Muscle Nerve*. 2000; 23, 1647-66.

13. Morse CI, Tolfrey K, Thom JM, Vassilopoulos V, Maganaris CN & Narici MV Gastrocnemius muscle specific force in boys and men. *J Appl Physiol*. 2008; 104, 469–474.

14. O'Brien TD, Reeves ND, Baltzopoulos V, Jones DA, Maganaris CN (2009a). Strong relationships exist between muscle volume, joint power and whole-body external mechanical power in adults and children. *Exp Physiol* 94(6), 731-8.

15. O'Brien TD, Reeves ND, Baltzopoulos V, Jones DA & Maganaris CN. Moment arms at the knee extensor mechanism in children and adults. *J Anat*. 2009b; 215, 198-205.

16. O'Brien TD, Reeves ND, Baltzopoulos V, Jones DA, Maganaris CN. Mechanical properties of the patellar tendon in adults and children. *J Biomech*. 2010a; 43, 1190-5.

17. O'Brien TD, Reeves ND, Baltzopoulos V, Jones DA & Maganaris CN. Differences in muscle-tendon structure and dimensions between adults and children. *J Anat*. 2010b; 216, 631-42.

18. Parker DF, Round JM, Sacco P & Jones DA. A cross-sectional survey of upper and lower limb strength in boys and girls during childhood and adolescence. *Ann Hum Biol*. 1990; 17, 199–211.

19. Pitt B, Dotan R, Millar J, Long D, Tokuno C, O'Brien T, Falk B. The electromyographic threshold in boys and men. *Eur J Appl Physiol*. 2015; 115, 1273-81

20. Round JM, Jones DA, Honour JW & Nevill AM. Hormonal factors in the development of differences in strength between boys and girls during adolescence: a longitudinal study. *Ann Hum Biol.* 1999; 26, 49–62.

21. Scheys L, Spaepen A, Suetens P, Jonkers I. Calculated moment-arm and muscle-tendon lengths during gait differ substantially using MR based versus rescaled generic lower-limb musculoskeletal models. *Gait Posture.* 2008; 28, 640-8.

22. Tsaopoulos DE, Baltzopoulos V, Maganaris CN. Human patellar tendon moment arm length: measurement considerations and clinical implications for joint loading assessment. *Clin Biomech.* 2006; 21, 657–667.

23. Van Praagh E, Ed. *Pediatric Anaerobic Performance*. 1998; Human Kinetics, Champaign, IL, USA.

24. Van Praagh E & Dor´e E. Short-term muscle power during growth and maturation. *Sports Med.* 2002; 32, 701–728.

25. Wakeling JM, Uehli K, Rozitis AI. Muscle fiber recruitment can respond to the mechanics of the muscle contraction. *J Roy Soc Interface.* 2006; 3, 533–544.

26. Waugh CM, Blazevich AJ, Fath F, Korff T. Can Achilles tendon moment arm be predicted from anthropometric measures in pre-pubescent children? *J Biomech.* 2011; 44, 1839-44

27. Waugh CM, Blazevich AJ, Fath F, Korff T. Age-related changes in mechanical properties of the Achilles tendon. *J Anat.* 2012; 220, 144–55.

28. Waugh CM, Korff T, Fath F, and Blazevich AJ. Rapid force production in children and adults: mechanical and neural contributions. *Med Sci Sports Exerc.* 2013; 45, 762-771.

29. Waugh CM, Theis N, Korff T, Baltzopoulos B. Developmental differences in muscle fascicle behaviour during walking: implications for movement efficiency? In the proceedings of the *International Society of Biomechanics.* 2015; abstract number: PO-0309.

30. Weide G, Huijing PA, Maas JC, Becher JG, Harlaar J, Jaspers RT. Medial gastrocnemius muscle growth during adolescence is mediated by increased fascicle diameter rather than by longitudinal fascicle growth. *J Anat.* 2015; 226, 530-41.

31. Wren TA & Engsberg JR. Normalizing lower-extremity strength data for children without disability using allometric scaling. *Arch Phys Med Rehabil.* 2007; 88, 1446-51.