©Journal of Sports Science and Medicine (2007) **6**, 292-304
http://www.jssm.org

Review article

Advances in paediatric strength assessment: changing our perspective on strength development

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Abstract
Our knowledge of the age and sex associated changes in strength during childhood and adolescence is relatively limited compared to other physiological parameters. However, those studies available on the age and sex associated change in strength are relatively consistent, especially for the lower limbs. Caution must be taken when transferring this knowledge to other muscle joints as the development in strength appears to be both muscle action and joint specific. Strength appears to increase in both boys and girls until about the age of 14 y where it begins to plateau in girls and a spurt is evident in boys. By 18 y there are few overlaps in strength between boys and girls. The exact age in which sex differences become apparent appears to be both muscle group and muscle action specific and there is a suggestion that sex differences in upper body strength occur earlier than lower body strength. What is less clear is the complex factors that contribute to the production of strength during childhood and adolescence. There are few well controlled longitudinal studies that have concurrently examined the influence of known variables using appropriate statistical techniques. Most studies have shown that maturation does not exert an independent effect when other factors, such as stature and body mass are accounted for. Also, the assumption that muscle cross-sectional area is the most important parameter in strength production does not hold when examined with other known variables. Consistently, stature appears to play a key role in strength development and this may be attributed to the strength spurt that has been linked to peak height velocity, and the muscle moment arm. Advances in technology have provided us with more accurate techniques to examine these explanatory variables but the complex interaction of neural, mechanical and muscular remains to be clearly identified from well controlled longitudinal studies.

Key words: Strength, children, muscle size, technology.

Introduction

Compared to other physiological parameters our understanding of the age and sex associated changes in strength are relatively limited, but development of equipment, and increased understanding of growth and maturation issues, have provided new insights into paediatric strength development. The term 'muscular strength' refers to a measure describing an individual's ability to exert maximum muscular force statically or dynamically (Osternig, 1986). Strength testing of children is performed routinely by researchers to monitor the determinants and development of strength through childhood but also by physiotherapists to assess the degree of muscle disability and to diagnose the rate of recovery. Therefore, a valid measurement method of muscle strength in children is critical. It is important for strength test administrators to be equipped with knowledge of the normal age- and sex-associated variations in strength and the factors attributable to that variation. Most laboratory and field based tests measure only the external development of force. Additionally, there are few paediatric studies that have examined muscle strength under electrically evoked conditions, probably associated with the ethical constraints of such tests. Therefore, unless otherwise stated any subsequent mention of strength shall be referred to as the measurement of voluntarily external force. It is also inappropriate to refer to all muscle strength movements as being a 'contraction'. It is more relevant to refer to strength movements as a muscle 'action' or 'moment' (the rotational effect of force). The term 'action' is favoured throughout this text as it refers to the state of the muscle, which is dependent upon the external force that is applied to that muscle via the skeletal system.

Historical assessment of strength

Early studies of strength development in paediatric subjects were primarily limited to field based tests such as number of sit ups/press ups in 1 minute or timed flexed or straight arm hang (Wilmore and Costill, 2004). Essentially these tests examined muscular endurance rather than muscle strength and may have clouded our understanding of age and sex associated changes in strength. The best example of this is the number of pull ups achieved by girls from 6-18 y which does not change, suggesting that strength in females does not increase with age. The suggestion that an 18 year old female has the same absolute strength as a 6 year old seems absurd, and this is a good case in point to demonstrate the importance of appropriate methods for measuring strength in the paediatric population. Most historical studies have used grip strength and other isometric actions to assess strength characteristics in children. The advantages of such techniques are well known (Wilson and Murphy, 1996), however there are distinct mechanical and neuromuscular differences between static and dynamic muscle actions. If the strength of the arms and legs are to be measured then it seems logical that they should be tested using dynamic strength tests since their everyday functions are dynamic and not static. Although isokinetic actions are not common everyday actions they provide additional insight into the strength of the muscle under dynamic conditions. Given the different neural and mechanical control strategies of concentric and eccentric muscle actions and the significance of these actions in everyday life, investigations of age- and sex-associated strength development should consider the ability of an individual to perform both types

Received: 02 March 2007 / Accepted: 18 July 2007 / Published (online): 01 September 2007

of action. The use of cable tensiometers and other isometric dynamometers can provide little information about the mechanical qualities of dynamic muscle actions (Osternig, 1986). Force, work and power are not easily measured if velocity is not kept constant because the changing mechanical advantage of the limb-lever system alters the force applied to the muscle through the range of motion, i.e. the load applied to the muscle is highest at the point of least mechanical advantage of the muscle at the extremes of the range of motion. Isokinetic dynamometers have become more commercially available in the last 20 years and have contributed to an increased understanding of the age and sex associated changes in dynamic muscle strength. The main feature of isokinetic exercise is that the resistance of the device precisely matches the movement speed applied by the individual so that velocity of movement stays constant. Isokinetic dynamometers measure torque, which is a function of muscle force (proportional to cross-sectional area (CSA) and the biomechanical advantage of the lever system (moment arm). From a physiological perspective, the factors that control the age and sex-associated variations in muscle strength are of great interest, yet much is still unknown about the factors that contribute to the observed age- and sex-associated differences in isokinetic strength.

Methodological considerations in paediatric strength testing

Paediatric subjects provide the physiologist with added challenges relating to varying rates of growth and maturation, and subsequently most testing methods and equipment have been devised with adult testing in mind. There has been an increased awareness amongst paediatric physiologists that most commercially available equipment needs adapting for meaningful data to be obtained. Some of our early understanding of the age and sex associated changes in strength may have been clouded by use of inappropriate equipment and protocols.

Choice of testing protocols with paediatric populations may be influenced by subjects, test equipment availability, cost and specificity of testing. Previous authors have suggested that the key issues relating to testing protocols should include the muscle group to be tested, joint angle, type of muscle action, velocity of muscle action and movement pattern (Blimkie, 1989; De Ste Croix et al., 2003). There are numerous generic protocol considerations when undertaking strength testing which are beyond the scope of this chapter. However, there are some which are specific to paediatric groups such as adaptation of equipment, stabilization and technique, habituation and learning effects, and safety. Advances in technology and techniques over the years, developed to quantify force production, have not come about without their fair share of methodological issues. For example, modifications to isokinetic dynamometers are required for the testing of children in order to isolate the target muscle group. Most authors have found the need to place a back pad behind young children to allow their lower leg to hang freely from the edge of the seat (Henderson et al., 1993; Weltman et al., 1988), or design an adjustable seat to allow for the various thigh lengths of children (De Ste Croix et al., 1999; 2002). Some dynamometers can be ordered with paediatric specifications such as adjustable seat length to accommodate the short femurs of children and short attachments, which may produce additional problems (e.g. need to adapt sensitivity settings). Unfortunately, several authors have neglected to describe changes to equipment, which may influence subject positioning and subsequent torque production (Gilliam et al., 1979; Weltman et al., 1988).

Other specific methodological issues of paediatric strength testing and reliability data have been covered in detail elsewhere (De Ste Croix et al., 2003) and it is beyond the scope of this review to address all of these issues. However, specific consideration needs to be given to familiarisation, especially if the protocol includes eccentric actions (Kellis et al., 1999). Children may be hesitant as the sensation of eccentric actions is novel and unique, as are the strategies employed by the nervous system to produce an eccentric action of maximum effort (Enoka, 1996). Other considerations such as warm up, the number of repetitions, range of motion, testing velocities and gravity correction procedures must all be based on paediatric models for meaningful data to be obtained.

Reliability of strength testing

In order for any strength measurement to be used as an objective and accurate measure of maximum strength it must be documented to be a reliable measurement tool. Poor reliability may lead to erroneous conclusions about the strength parameter being measured. Experimental error can be minimised effectively by standardisation of test protocols that will provide greater sensitivity to detect biological sources of variation in a child's ability to exert maximum muscular effort.

An habituation period is critical for paediatric strength testing as this essential period of learning facilitates a phase in which the specific movements, neuromuscular patterns and demands of the test become familiar to the individual. Previous studies (Deighan et al. 2003; Blimkie, 1989) have reported good reliability in repeated isokinetic actions of the knee in 6 to 8 year old (extension $r = 0.95$; flexion $r = 0.85$); isokinetic actions of the elbow in 9/10 y (extension $r = 0.97$; flexion $r = 0.87$) and isometric hand grip data in 8-11y ($r = 0.92$). Others have reported limits of agreement showing no systematic difference in knee and elbow peak torque measured on two separate occasions (Deighan et al., 2003). A recent study on prepubertal soccer players has reported systematic bias in concentric and eccentric knee torque, although these improvements, 3 to 7 %, were relatively small (Iga et al., 2006). It would appear that strength testing in children, irrespective of muscle action or muscle joint assessed, has a test-retest variation of around 5-10 %.

It is difficult to compare results across studies as different statistical methods, many of which are questionable, have been used to assess reliability that is also protocol, measured parameter and dynamometer specific. However, the available literature currently supports the reliability of strength testing with children but suggests that extension movements are more reliable than flexion movements and that concentric actions are more reliable than eccentric actions.

Eccentric testing in paediatric populations

Eccentric actions occur in everyday life as often as concentric actions. For example, the knee extensors play a significant role in shock absorption during walking, running and jumping and the knee flexors play the role of a 'brake' as the knee extends during walking, kicking and running. The characteristics and control mechanisms of these two actions are very different, therefore the assessment of both types of action is essential for a complete understanding of strength development. It is possible that the limited information on eccentric strength capabilities of children may be due to the concern that eccentric testing with its potential for high muscle force production might predispose children to higher risk of muscle injury or delayed onset of muscle soreness. However, there is no reason to expect greater muscle injury with eccentric actions in children compared to adults or other forms of muscle testing, provided they are given sufficient warm-up and familiarisation (Blimkie and Macauley, 2001). Although still expensive, the greater choice in commercially available isokinetic dynamometers has allowed the researcher to isolate eccentric muscle actions during a range of joint movements. Even though eccentric data on children is currently sparse, the technological advances in isokinetic dynamometry has opened up avenues to explore the age and sex associated changes in eccentric muscle actions, as well as to examine the eccentric/concentric ratio to examine joint stability (De Ste Croix et al., 2007).

Eccentric/concentric ratio and knee stability

Conventionally, the hamstring/quadriceps ratio is calculated by dividing the torque of knee extensors and flexors at identical angular velocity and contraction mode. However, previous authors have suggested that to evaluate muscular balance of the knee the eccentric/concentric actions of the knee flexors (KF) and knee extensors (KE) should be examined (ECC_{KF}/CON_{KE} or CON_{KF}/ECC_{KE} ratio) and referred to as a functional ratio rather than the conventional ratios often used (ECC_{KF}/CON_{KF} or ECC_{KE}/CON_{KE} ratio) (Aagaard et al., 1998; Gerodimos et al., 2003). Examining reciprocal muscle group ratios provides information on knee function, injury risk and most importantly, knee joint stability (Gerodimos et al., 2003). One previous study that used conventional ratios of the knee demonstrated that an ECC/CON ratio of less than 60 % at 1.04 rad·s^{-1} represents a 77.5 % probability of knee injury in elite soccer players (Dauty et al., 2003). There appear to be no available data on relative risk of injury in non-elite performers and from functional ratios.

As dictated by the force-velocity relationship, the ECC/CON ratio will increase as angular velocity increases (Colliander and Tesch, 1989; Griffin et al., 1993) but if measured at one velocity it is possible to make comparisons of peak torque ratios between age groups and sexes. Meaningful interpretation of the ECC/CON ratio in relation to age and sex have been problematic due to the order of action cycling in the isokinetic protocol. For example, during ECC/CON cycles the ECC action may theoretically potentiate the following CON action (Hildebrand et al., 1994; Mohtadi et al., 1990). Gerodimos et al. (2003) reported a non-significant age effect on functional ratios between 12-17 y old trained male basketball players. It is not known whether there is a difference between the ECC/CON ratios of children and adults into the mid 20's where muscle mass of the upper body is still developing in males. It cannot be assumed that the relationship between CON and ECC actions is the same across ages during childhood and puberty because children may have immature neuromuscular systems due to the incomplete myelination of nerve fibres during childhood (Brookes and Fahey, 1985). However, probably due to ethical issues surrounding invasive testing procedures, the neuromuscular system of children is poorly understood and requires further investigation.

Dvir (1995) proposed that ECC_{KF}/CON_{KE} ratios derived from low/medium test velocities are typically within the range of 0.95 – 2.05 for healthy adults. The few studies that have measured the ECC/CON ratio in children have all found significantly higher ECC compared to CON strength (Calmels et al., 1995; Hildebrand et al., 1994; Kellis et al., 1999; Seger and Thorstensson, 1994) with ratios ranging from between 1.17 at the slowest velocity to 1.47 at the highest velocity. However, in these studies the ECC/CON ratio has been determined using ECC_{KE} and CON_{KE} rather than functional ratios.

It has been suggested that sex differences in adults in the conventional ECC/CON ratio of the knee joint are due to differences in percentage motor unit activation (%MUA) during maximal voluntary actions, with women having a lower %MUA than men during CON actions, (Griffin et al., 1993; Westing and Seger, 1989) but not ECC actions, possibly because the actions have separate neural control mechanisms (Enoka, 1996). Others have suggested that the sex difference is due to a lower capacity for CON rather than a higher capacity for ECC force production in females (Seger and Thorstensson, 2000). There is contrary evidence, however, in the form of a superior ability of females compared to males in utilising stored elastic energy in the muscle-tendon unit (Komi and Bosco, 1978). One recent study has examined the age-and-sex associated changes in the functional ratio in prepubertal children, teenagers and adults (De Ste Croix et al., 2007). In this study, females' functional ratio was significantly lower than males' at both slow and fast velocities and was a product of lower concentric torque as opposed to high eccentric torque producing capability. This is in conflict with previous data that suggested females have higher eccentric force producing capability compared to males. Adults demonstrated significantly lower CON_{KF}/ECC_{KE} than teenagers at 0.52 rad·s^{-1} and lower than the prepubertal and teenager groups at 3.14 rad.s^{-1}. However, for ECC_{KF}/CON_{KE} at 3.14 rad·s^{-1} prepubertal ratios were significantly lower than teenagers and adults. These data have highlighted for the first time that during fast velocity movements prepubertal children have a lower capacity for generating eccentric compared to concentric torque. The lower CON_{KF}/ECC_{KE} ratio in adults appears to be due to a greater ability to generate large eccentric torques during slow and fast movement velocities. Longitudinal data are needed to examine how the functional ratio changes throughout the pubertal years.

Statistical analysis – the influence of adjusting for body size on strength development

It has become common in the literature to express strength in absolute terms, with isometric data expressed in newton (N) and isokinetic data expressed in newton metre (Nm). In the study of muscle strength with growth and maturation, comparisons are made between individuals of different sizes. It is therefore important that a size-free strength variable is used for interpretive purposes. From a strength perspective the key issue to be addressed when scaling for body size differences are the body size variable with which to scale the performance variable and the method to be employed. For a detailed review of adjusting for body size on strength variables the reader is directed to a paper by Jaric (2002).

The most commonly used technique in the strength literature to partition out differences in size is the ratio standard with body mass as the most widely used denominator. However, stature and fat-free mass have also featured as covariates. Others have used allometric scaling techniques to examine the theory that muscle cross-sectional area and strength are a function of second power of height. The b exponents identified in the study of Kanehisa et al. (1995) ranged from 2.4 to 3.6, which were significantly higher than the predicted 2.0 and the authors concluded that strength should be scaled to stature$^{3.0}$, or body mass.

Three longitudinal studies have used multilevel modelling to examine a number of known covariates to determine their influence on the age and sex associated changes in muscle strength (De Ste Croix et al., 2002; Round et al., 1999; Wood et al., 2004). Most authors currently support the view that suitable scaling factors should be derived from careful modelling of individual data sets, and therefore be sample specific rather than adopting assumed scaling indices.

Age and sex associated changes in strength: a historical perspective

It is clear that many factors interact to produce the expression of strength. Awareness of the anthropometric, neurologic, hormonal, age and sex -associated changes in skeletal muscle strength is important from childhood to adulthood. While there is abundant literature focussing on determinants of strength development, few studies have used common age ranges, muscle groups, testing protocols and muscle actions, making comparisons difficult.

Most early strength development studies examined isometric forces generated from handgrip data. It has been suggested that strength measured as isometric or dynamic force reflects the same relative strength between individuals regardless of the type of test method (Froberg and Lammert, 1996). However, dynamic actions are far more reflective of dynamic muscle properties, themselves a function of neuromuscular factors and fibre type composition, more so than isometric actions.

Isokinetic assessment has primarily been recommended for strength testing as maximal force is applied during all phases of the movement at a constant velocity (Stocker et al., 1996). The isokinetic mode is also safe to use with children because there is minimal risk of muscle and joint injuries, which can result from efforts to control the load if using free weights in 1-Repetition Max testing (Osternig, 1986). Isokinetic assessment also permits quantification of a variety of muscle function indices such as peak and average torque, joint angle of peak torque, work and power. Different velocities of movements can be tested, allowing evaluation of the force-velocity characteristics of various muscle groups. It is also possible to examine bilateral dominance and the hamstring/quadriceps ratio has been investigated in both adult and paediatric populations (Faro et al., 1997). The majority of previous paediatric studies have examined concentric isokinetic knee extension and flexion torque (Alexander and Molnar, 1973; Gilliam et al., 1979; Housh et al., 1984; 1996; Tabin et al., 1985; Pfeiffer and Francis, 1986; Rochcongar et al., 1988) with fewer studies investigating elbow extension and flexion (Alexander and Molnar, 1973; Deighan et al., 2002a; Wood et al., 2004, 2007) and single studies examining hip torque (Burnett et al., 1990), plantar flexor torque (Falkel, 1978), shoulder torque (Alexander and Molnar, 1973) and trunk torque (Balageu et al., 1993). Many paediatric studies have examined elite athletes but few studies have included female subjects or examined clinical populations (McCubbin and Shasby, 1985; MacPhail and Kramer, 1995).

Age and sex related changes

Most of our early understanding of the age and sex associated development in strength was restricted to physical performance tests. Field tests tend to lack measurement sensitivity and therefore we are often left with a high percentage of zero scores. As strength testing is dependent upon motivation field tests may not be sensitive enough to detect the more generalised gains in strength. A good example of this is the data presented from the National Child and Youth Fitness Study (1985) in which 60 % of girls aged 10-18 y failed to do one pull up. As field tests require the resistance or movement of the individual body mass it follows that children with a larger mass will be disadvantaged. Data that have used pull-ups as the criteria for determining sex differences in muscle strength has clouded our understanding of strength development during growth and maturation. It is hardly surprising therefore those correlations between strength measurements using field tests and dynamometers are often non-significant in paediatric populations.

It is also important to bear in mind that our understanding of the development of strength with age will be influenced by the nuances of the testing procedures used, such as subject positioning, degree of practice, level of motivation, lateral dominance and level of understanding about the purpose and nature of the test.

When examining data relating to changes in strength due to growth and maturation it is essential to remember that the majority of data have been derived from isometric testing. Children may not produce maximal force during isometric actions, and this has been attributed to inhibitory mechanisms that preclude children from giving a maximal effort due to a feeling of discomfort caused by the rapid development of force during isometric actions. Therefore the whole motor pool may not be activated due to a reduction in the neural drive under high tension loading conditions.

In his comprehensive review Blimkie (1989) notes that while there are a number of studies examining strength development, few studies show commonality in assessed age ranges, muscle groups tested, methodology used, muscle action studied and physiological condition under which muscles were tested and this view still holds today. The abundant literature on strength during childhood has been derived from cross-sectional studies and there are few longitudinal studies available spanning childhood and puberty.

Data from isometric actions indicate that both boys and girls strength increase in a fairly linear fashion from early childhood up until the onset of puberty in boys (around 13 y) and until about the end of the pubertal period in girls (around 15 y). The marked difference between boys and girls is caused by a strength spurt in boys throughout the pubertal period, which is not evident in girls. Girls' strength appears to increase during puberty at a similar rate to that seen during the prepubertal phase and then appears to plateau post puberty. There is some disagreement about the age at which sex differences become evident. However, although conflicting evidence is available it is generally conceded that before the male adolescent growth spurt there are considerable overlaps in strength values between boys and girls. By the age of 16/17 y very few girls out perform boys in strength tests, with boys demonstrating 54 % more strength on average than girls.

Throughout childhood and puberty, particularly in males, isometric elbow flexor and knee extensor strength are highly correlated with chronological age. Although there are some data on the age related changes in the knee extensors and flexors for children the trends affecting these muscle groups are limited. In line with isometric data most cross-sectional studies of changes in dynamic strength have demonstrated a significant increase with age. For example, increases in males and females' absolute knee extensor (314 % and 143 %) and flexor (285 % and 131 %) strength have been noted from the ages of 9-21 y (De Ste Croix et al., 1999).

Some studies have suggested that age exerts an independent effect on strength development over and above maturation and stature (Maffulli et al., 1994). Others have recently indicated that once muscle CSA is accounted for using a multilevel modelling procedure that age explained a significant amount of the additional variance in isometric elbow extensor peak torque (Wood et al., 2004). It was suggested that this positive age term may be explained by the shared variance with maturation as maturation was not included in the model. However, another longitudinal data set, using multi-level modelling, has suggested that age is a non-significant explanatory variable on isokinetic knee torque once stature and mass are accounted for (De Ste Croix et al., 2001). This is probably attributable to differing rates of anatomical growth and maturation, which vary independently, and thus their effects on strength do not correlate simply with chronological age. It would appear that although there is a strong correlation between strength and age a large portion of this association is probably attributable to the shared factors of biologic and morphological growth rather than age itself.

Some authors have suggested that sex differences in muscle strength are evident from as early as 3 years of age. As previously mentioned there is little consensus about when sex differences in muscle strength become apparent. Some studies have shown clear sex differences by 13-14 years of age. A recent longitudinal study using multilevel modelling to control for known covariates suggested that there are no sex differences in dynamic strength up until the age of 14 y. After 14 years of age boys out perform girls in muscle strength irrespective of the muscle action examined or with body size accounted for (De Ste Croix et al., 2002).

Isometric data suggests that sex differences in strength are relatively greater in muscles of the upper compared to the lower body in children. Gilliam et al. (1979) reported no significant sex difference in 15-17 y old knee extension peak torque but sex differences were apparent for the elbow extensors. These data are supported by a more recent study of 9-18 y old volleyball players, which reported no significant difference in isometric and isokinetic knee extension strength but a significant difference in elbow flexor strength in postpubertal children (Schneider et al., 2004). This has been attributed to the weight-bearing role of the leg muscle. It has also been suggested that during growth and maturation boys use their upper body more than girls through habitual physical activities (such as climbing). This sociocultural explanation has recently been brought into doubt as there is no overlap in strength between physically active girls and sedentary boys as would be expected if this premise were true (Round et al., 1999).

For developmental physiologists understanding the complex interaction of factors during growth and maturation that may contribute to the age and sex associated change in strength development is challenging. Historically, simple anthropometric characteristics (such as stature and body mass) have been explored as possible explanatory variables for the age and sex associated changes. As technologies have become more advanced we have the possibility to explore muscle size and moment arm using magnetic resonance imaging, muscle angle of pennation and physiological cross sectional area using ultrasonography, motor unit recruitment using electromyography, and hormonal analysis using biochemistry. Our ability to concurrently examine possible explanatory variables, using sophisticated techniques, may have changed our understanding of the contributory factors of strength development during childhood and adolescence. There are few longitudinal studies that have examined these variables concurrently using appropriate scaling methods. The following sections focus on the role played by the factors associated with the development of muscle strength.

Influence of stature and mass

The influence of gross body size on strength development has been examined in several studies. Stature and mass are traditionally the size variables of choice because they can be quickly and easily measured. Early longitudinal studies demonstrated that isometric strength per body mass varied only slightly during childhood and through puberty in girls. In contrast, around the time of boys' peak height velocity (PHV), i.e. age 14 y, there was an increase in strength per body mass in boys, which was still increasing by age 18 y.

Body mass has been found to be highly correlated with maximal voluntary isometric strength of elbow flexors and knee extensors in males aged 9 to 18 y (Blimkie, 1989). However, age-specific correlation coefficients between strength and body mass for males are generally low to moderate during the mid-childhood years, tend to increase then peak during puberty and abate in the late teens. Data on this relationship are scarce for females but moderate positive coefficients between strength and body mass for females during the prepubertal years and at the onset of puberty and low correlations at the end of puberty and during puberty have been reported (Blimkie and Macauley, 2001; De Ste Croix, 1999). Others have found the relationship between female strength and body mass to be high during teen years and to decline during young adulthood (Deighan et al. 2002a, Hildebrand et al, 1994). When related to shorter periods of growth (in which the range of the anthropometric variable in question is small), correlations become weaker. This reliance of the correlation coefficient on the characteristics of the sample means that comparison of correlation coefficients between studies is made difficult. It is worth noting here that when isokinetic knee extension and flexion torque was adjusted for body mass using the ratio standard the rate of change in strength between 9-21 y of age was underestimated compared to mass-adjusted data using allometric techniques (De Ste Croix et al., 1999).

It is well recognised that peak strength velocity occurs about a year after PHV (11.4-12.2 y in girls and 13.4-14.4y in boys). It has been suggested that the difference in attainment of PHV and subsequent peak strength gains account for the lack of a significant sex difference in strength at 14 y. Girls will be in the phase of peak strength gains at 14y whereas boys will not have experienced the strength spurt.

Three recent longitudinal studies, examining isometric and isokinetic strength respectively, have used multilevel modelling to examine the factors related to strength development. Round et al. (1999) reported that isometric knee extensor strength in girls increased in proportion to the increase in stature and mass in 8-13 y old. De Ste Croix et al. (2001) also demonstrated that stature and mass are significant explanatory variables of isokinetic knee extension and flexion torque in 10-14 y old. This is further reinforced by Wood et al. (2004) who demonstrated a significant influence exerted by stature on the development of isometric and isokinetic elbow flexion and extension on 13-15 y old. Conflicting data are available and the study of Round et al. (1999) suggested that in boys the strength of the knee extensors was disproportionate to the increase in body size. This difference was explained once testosterone was added to the multilevel model.

Although simple body dimensions appear to be important in the development of strength with age only 40-70 % of the variance in strength scores of 5 to 17 y-old children could be accounted for by age, sex, stature and body mass leaving a large portion of the variance unexplained.

Maturation and hormonal influences on strength development

Early studies indicated that maturation, determined using Tanner's (1962) indices of pubic hair development, is a better predictor of 1-Rep max isotonic maximal knee extension and flexion than simple chronological age. A recent longitudinal study of 10-14 y-old indicated that maturation was a non-significant explanatory variable in the development of isokinetic knee extension and flexion, once stature and mass were accounted for, using multilevel modelling procedures (De Ste Croix et al., 2002). However, the authors do acknowledge that their sample consisted of a narrow range of maturational stages. Supporting data are available with previous studies indicating that maturation does not exert an independent effect upon isometric strength development in 10-18 y old athletes (Maffulli et al., 1994) and 12-14 y old football players (Hansen et al., 1997).

An important consideration regarding the development of muscle function is the effect of endocrine adaptations typical of sexual maturation such as increased levels of testosterone ([T]) and growth hormone (GH). There is both direct and indirect evidence to demonstrate the association between [T] and strength development during puberty.

[T] levels accelerate from a modest 4 fold increase during the early stages of puberty to a rapid 20 fold increase in mid-late puberty in boys (around Tanner stage 3). It is not surprising that [T] levels appear to coincide with the divergence of strength between boys and girls as circulating [T] begins to rise one year before PHV, increasing steadily and reaching adult levels about 3 years after PHV. Testosterone has been shown to stimulate anabolic processes in skeletal muscle and appears to be the principal hormone responsible for the development of strength. As previously stated, Round et al. (1999) suggested that [T] accounts for the sex difference that exists in isometric strength even after making allowances for body size. Full analysis showed that there was an increase of 0.7 % in isometric knee extension strength for every $nmol.L^{-1}$ of circulating [T]. The analysis showed that the young men in the sample were 15 to 20 % stronger as a result of the [T] than might be expected from their overall body stature. In contrast, the same analysis for biceps showed that sex differences could not be fully accounted for by the effects of [T] in teenage boys. These authors speculated that the linear measure inserted into the model for biceps should be humerus length as opposed to stature. Their plausible suggestion was based on the well-known increase in the upper limb girdle dimensions in boys during puberty that provides an additional stimulus for muscle growth with the direct action of [T] in the muscle. Jones and Round (2000) indicated that increasing levels of oestrogen in the girls causes inhibition of muscle growth as a result of a speedier skeletal maturation, which removes the lengthening stimulus for muscle growth.

Ramos et al. (1998) also reported that body mass did not eliminate the age effect in isokinetic peak torque in boys and that [T] increased with age in boys but not in girls. This increase in [T] preceded the gains in muscle strength but more importantly there was a moderate positive correlation (r = 0.64) between serum [T] and isokinetic angle specific torque.

Measuring muscle size – magnetic resonance imaging

It has always been assumed that the size of the muscle, in particular physiological muscle cross-sectional area (pCSA) is the most important parameter in the development of force in adults. The role that muscle CSA (mCSA) plays in the production of force in the growing child has also been extensively examined, based on the relationship between force production and strength in adults. The difficulty with paediatric subjects is the influence of other explanatory variables that relate to growth and maturation and subsequently the production of force in the growing child may not simply be prescribed to the size of the muscle.

When examining studies that have explored the role that the mCSA has on strength development during growth and maturation the technique used to determine muscle size must be examined. When measuring mCSA in children for research purposes the technique used should be non-invasive with no potential side effects. Many studies with children have used anthropometric techniques to estimate mCSA because they are low cost, equipment is easily accessible and often easily portable, the measurement protocols take little time and few personnel, which is important if the number of subjects is large. Every effort should be made to ensure accuracy by standardising the technique with measurements always made by the same trained observers. This is particularly important if measurements are to be taken over time, in order to safeguard the validity and usefulness of the data.

At the simplest level, coaches have been known to take circumference measurements alone to estimate mCSA but circumference measurements ignore the obvious fact that limb circumference is influenced by fat and bone cross-sections as well as muscle, such that a larger circumference need not mean a larger muscle. Efforts have been made to take into account the contribution of fatness to the circumference measurement by incorporating skinfold thickness into the equation (Jones and Pearson, 1969).

The techniques described by Jones and Pearson (1969) are the most widely used anthropometric technique for estimating thigh muscle volume plus bone in children although more recent equations by Housh et al. (1995) for determining total mCSA plus bone have also become popular. The main problem with both of these techniques is that the regression equations have been derived from adult data and therefore cannot be confidently applied to children. Work exploring the reliability of the Jones and Pearson technique in children, comparing the anthropometric technique to muscle volumes determined using Magnetic Resonance Imaging (MRI), found that the anthropometric technique underestimates lean thigh volume by 31 % (range 14-46 %). Limits of agreement further support this conclusion by identifying a consistent bias towards an underestimation in total thigh volume. Therefore while anthropometric estimates may be valid for a 'snapshot' of mCSA plus bone or for characterising various populations, they are not acceptable for monitoring changes over time (Housh et al 1995). Anthropometric techniques may be a useful way of approximating mCSA plus bone on a one-time basis but not used in paediatric studies examining changes during growth and maturation.

Radiography is a technique, which can potentially provide estimates of mCSA, but due to the radiation exposure required to produce well-defined radiographs, ethical considerations mean this technique is unsuitable for use with children. In any case, conventional radiographs depict a three-dimensional object as a two dimensional image so that overlying and underlying tissues are superimposed on the image which makes determination of mCSA difficult.

Computerised Tomography (CT) overcomes this problem by scanning thin slices of the body with a narrow x-ray beam, which rotates around the body, producing an image of each slice as a cross-section of the body and showing each of the tissues in a thin slice. Unlike conventional radiography, CT can distinguish well between muscle, bone and fat. Children are particularly sensitive to radiation therefore this technique is contraindicated in children.

Ikai and Fukunaga (1968) made the first measurement of strength per mCSA using ultrasonography with children. The technique has also been applied in studies concerned with fibre pennation of the quadriceps muscle after training, mCSA of the calf of the dominant leg of junior soccer players and the effect of strength training on upper arm mCSA of children. One of the major issues of ultrasonography is the difficulty in distinguishing tissue boundaries and the difficulty in determining individual muscles/muscle groups.

MRI is a technique that in recent years has offered exciting opportunities for the study of gross structure and metabolism of healthy and diseased muscle. With MRI ethical constraints are avoided unlike CT and radiography. MRI can accurately measure anatomical mCSA, distinct muscle groups can be differentiated and it appears to be more suitable than other imaging techniques used for the examination of mCSA. With unparalleled picture clarity it is possible to differentiate individual muscle/muscle groups and identify both intramuscular fat and blood vessels. Despite the financial limitation numerous studies have recently used MRI with paediatric populations to determine muscle volume and mCSA (Deighan et al., 2006; De Ste Croix et al., 2002; Wood et al., 2004, 2007).

Site of mCSA measurement

A methodological problem with many previous studies of force or torque per mCSA with growth and maturation is that the optimal site for the measurement of maximum mCSA within and between subjects has not been clearly identified. Instead, an arbitrary location on the limb has been used for mCSA determination of mid femur in the case of thigh muscles and mid humerus in the elbow flexors and extensors. Adult data suggests that for the knee extensors 2/3 upper femur height and 1/3 lower femur height for the knee flexors should be used as the site of maximal mCSA. De Ste Croix et al. (2002) measured the maximal mCSA of each individual subject using MRI and found maximal thigh mCSA to occur between 51 and 69 % of ascending femur length in 10-14 y old. A recent cross-sectional study, using MRI determined thigh and arm mCSA in 9 y old, 16 yold and adults, demonstrated that there are age differences in the location of maximal mCSA of the elbow extensors (Deighan et al., 2006). In order for age, sex and muscle group comparisons to be made, an optimal site of mCSA needs to be individually determined for the paediatric population. Therefore the site chosen to determine mCSA should be taken into account when interpreting the age and sex associated development in mCSA.

Age and sex associated development in mCSA

CSA of muscle fibres reach their maximal adult size by 10 y in girls and 14 y in boys. Although muscle fibres appear to reach their maximal CSA early in childhood this does not mean that muscle has reached its maximal length as muscle will continue to grow in length simultaneously with growth in limb length segments.

The Harpenden Growth study examined age and sex differences in radiographically determined upper arm and calf widths of British children from infancy to age 18 y. Boys' muscle widths appeared greater than those of girls during childhood but the difference was small. MRI studies have also found no significant sex difference in knee and elbow mCSA up until 13 / 14 y. A large cross-sectional study using MRI demonstrated a significant age effect in elbow mCSA up until 24 y (Deighan et al., 2002a). These data indicate that from 9 – 24 y elbow extensor and flexor mCSA increases 207 and 210 % in males and 65 and 78 % in females respectively. By adulthood CT determined muscle size found that the mCSA of the arm and thigh of adult females is around 57 % and 72.5 % than that of adult males.

According to Blimkie (1989) "it is likely that quantitative differences in muscle width account for a large proportion of the observed age and sex differences in strength development during childhood and adolescence" (p127). It is important at this point to reconsider that there have been variations in the methods used to measure both strength and muscle size. The relationship between muscle size and strength during growth has been examined by measuring muscle widths, muscle volume and mCSA. It is also important to note that most studies have reported anatomical mCSA due to the difficulties in determining physiological mCSA.

There are considerable data that support the contention that differences in muscle size account for differences in muscle strength during growth. One of the earliest studies examined the relationship between isometric elbow flexion strength and mCSA determined by ultrasonography in 12 to 29 y-old (Ikai and Fukunaga, 1968). Although correlation coefficients were not given, the authors indicated that strength 'is fairly proportional' to elbow flexor mCSA regardless of age or training status. The relationship appeared weaker for girls than boys. Others (Deighan et al. 2002a; 2002b; Round et al. 1999) have reported a strong positive correlation between muscle size, and isometric knee strength (r = 0.87), isokinetic knee strength (r = 0.73), isokinetic elbow strength (r = 0.82) and isokinetic triceps surae strength (r = 0.91). In addition, based on grip strength data on children, the sex related growth curve patterns for body muscle are virtually identical to those for strength suggesting a strong association between muscle growth and gains in strength. Numerous longitudinal studies (Wood et al. 2004; De Ste Croix et al. 2002) have shown that mCSA is a significant explanatory variable in the age associated development in strength when examined as an independent covariate. However, it would appear that when additional variables are examined concurrently alongside mCSA its influence is reduced or disappears.

Age differences in strength per mCSA

There is still some debate about whether strength per mCSA increases with age. Early studies demonstrated increasing strength per mCSA from age 7 to 13 y. Also, Kanehisa et al. (1995) suggested that isokinetic strength per mCSA, measured using ultrasonography, was greater in older age groups (18 y) than younger age groups (7 y) in every muscle group measured. It was hypothesised that children in the early stages of puberty may not develop strength in proportion to their muscle anatomical CSA. It is likely that the deficiency in strength per mCSA in the younger age groups might be the result of a lack of ability to mobilise the muscle voluntarily. The same group of authors found that the isometric strength of the ankle dorsi flexors and plantar flexors per mCSA measured by ultrasonography in boys and girls aged 7 to 18 y was significantly greater only for plantar flexion in 16-18 y old boys compared to the other groups. In a comprehensive cross-sectional study others have reported a significant increase in isokinetic knee and elbow torque per MRI determined mCSA from 9-16 y but no significant difference from 16-24 y (Deighan et al., 2002a; 2002b). Further investigation is required to establish whether these differences in torque per mCSA are due to biomechanical or neuromuscular factors. What these data do suggest is that torque per mCSA of the elbow and knee extensors and flexors are at adult levels by 16 y of age. Conflicting data are available and Tolfrey et al. (2003) recently reported that despite smaller MRI determined triceps surae mCSA early pubertal boys torque scaled to muscle size is not different from adult males. These conflicting data emphasise the need to measure the strength per mCSA ratio in a variety of muscles as the strength development characteristics of one muscle or group of muscles may not be the same as another, even within the same joint.

Sex differences in strength per mCSA

Debate surrounds whether sex differences exist in strength per mCSA. Early work reported that absolute isometric strength differences between sexes disappeared when data were normalised to anthropometric muscle (plus bone) CSA in 9-12 y old. Sunnegardh et al. (1988) showed that boys had significantly greater torque per CSA than girls at 13 y. Deighan et al. (2002a) recently reported significant sex differences in isokinetic elbow flexion per mCSA in 9/10 y old and 16/17 y old. These studies are in contrast to others that have demonstrated similar strength to mCSA ratios between sexes (Deighan et al., 2002b; Ikai and Fukunaga 1968; Wood et al., 2004). Deighan et al. (2002b) reported no significant sex differences in isokinetic torque per mCSA of the knee extensors and flexors and elbow flexors in 9/10 y-olds, 16/17 y-olds and adults. Using multilevel modelling procedures on longitudinal data Wood et al. (2004) also reported that gender effects for isokinetic elbow extensors and flexors became non-significant once mCSA was controlled for. The majority of recent studies would lead us therefore to the conclusion that there is no significant sex difference in strength per mCSA irrespective of the muscle joint or action examined. It would appear that factors in addition to mCSA may account for the age and sex associated development in strength.

For example, the peak gain in muscle strength in boys occurs more often after peak stature and mCSA velocity but there is no such trend for girls. Therefore, particularly in boys there may be factors other than mCSA that affect strength expression during puberty. Also, it has been shown that the sex differences that occur in strength of boys and girls of the same stature cannot be accounted for by muscle size alone. A longitudinal study of upper arm area and elbow flexor strength have shown that boys have muscles ~5 % greater in area but which produce ~12 % more strength. Others have indicated that mCSA is a non-significant explanatory variable once stature and mass are accounted for (De Ste Croix et al., 2001).

Peak muscle mass velocity has also been shown to occur at an average of 14.3 y, whereas peak strength velocity appeared at age 14.7 y. This supports the view that muscle tissue increases first in mass, then in functional strength. Consequently, this would seem to suggest a qualitative change in muscle tissue as puberty progresses and perhaps a neuromuscular maturation affecting the volitional demonstration of strength.

Biomechanical factors – the muscle moment arm

The mechanical advantage of the musculoskeletal system is variable across different muscle groups and is considered unfavourable because the measured force or torque is somewhat smaller than the corresponding tension developed in the muscle tendon. Another unfavourable biomechanical influence on the measured force lies in the internal muscle architecture, i.e. the greater the angle of pennation to the long axis of the muscle, the smaller proportion of force in the muscle fibres that is transmitted to the muscle tendon. The age-associated relationships between these factors have not yet been extensively investigated in children.

It is probable that small differences between subjects in the location of the centre of rotation of the joint or in the length of the lower limb could contribute to the observed variability in the ratio of muscle strength to mCSA. It is difficult to account for biomechanical factors but some authors have divided strength values by the product of mCSA and stature ($Nm\cdot cm^{-3}$), i.e. the product of mCSA and possible differences in moment arm length or mechanical advantage which they assumed to be proportional to stature. There are few published data on the relationship between strength per mCSA and mechanical advantage covering different age groups, both sexes and different muscle groups but it seems sensible to correct strength for possible differences in mechanical advantage, especially if comparing children of different sizes by normalising to mCSA*limb length (LL) (Blimkie and Macauley, 2001). One of the major assumptions with using this method is that the relationship between the muscle moment arm and limb length are proportional.

Numerous authors have demonstrated a moderately strong, positive correlations between stature and isometric torque per mCSA for the elbow flexors (r = 0.67) and knee extensors (r = 0.57); isokinetic knee extensors (r = 0.85) and flexors (r = 0.84); and isokinetic elbow extensors (r = 0.79) and flexors (r = 0.80) (Deighan et al., 2002a). Kanehisa et al. (1994) found that isokinetic torque was significantly correlated to mCSA*thigh length (r = 0.72 to 0.83). These data suggest that at least part of the age associated variability in voluntary strength may be attributed to differences in mechanical advantage that occur with growth.

Blimkie (1989) reported that age effects were the same whether dividing torque by the product of mCSA and stature or just mCSA. Young adults have been found to have significantly higher ratios of isokinetic knee extension torque per unit of mCSA*thigh length than children with the difference becoming greater with increasing velocity of movement. Deighan et al. (2002a) suggests that the influence of mechanical advantage on the development of isokinetic strength may be muscle group specific. Data showed a non-significant age effect for the elbow extensors and flexors but a significant difference between 9/10 y-olds and 16/17y-olds in knee extension and flexion torque per mCSA*LL. The knee data suggest that mCSA*LL alone cannot account for the age differences in strength. It is difficult to attribute physiological reasons to the muscle group differences but it is possible that part of the explanation may lie in the differing function of the arms and legs. For example, there is some evidence to suggest that the extent of motor unit activation of the arm muscles remains essentially unchanged with growth but increases in the muscles of the thigh.

Early work indicated that sex differences in absolute torque remain statistically significant, although diminished, when expressed per unit mCSA*thigh length. Kanehisa et al. (1994) reported no significant sex differences in young children but that sex differences become apparent in adulthood when expressing torque per mCSA*LL. A recent study by Deighan et al. (2002a) reported non-significant sex differences for the knee and elbow extensors and flexors in torque per mCSA*LL in 9/10 y old, 16/17 y old and adults. Recent data therefore shows that sex differences, at least for dynamic strength, can be accounted for by the product of mCSA and limb length. Only 1 study appears to have longitudinally examined leverage in children from isometric actions and using MRI to determine mCSA and muscle moment arm using a geometric model (Wood et al., 2007). Wood et al. (2007) reported no significant age or gender effect on muscle moment arm length in the elbow from 13-15 y. However, using multi-level modelling mechanical advantage significantly contributed to the explanation of torque variance at 10° of flexion. The authors note, however, that both muscle length and architecture were not determined in this study and further investigation of physiological mCSA is needed to enhance our understanding of strength development in children.

There has been speculation that the angle of muscle pennation plays a role in the group differences in strength per mCSA (Blimkie, 1989). Conventional scanning techniques all measure mCSA at right angles to the limb, i.e. anatomical mCSA. However, the maximum force a whole muscle or muscle group can produce is a function of the tension generated by each individual fibre in the direction of the muscle's line of pull. Most muscle groups that are tested in humans are pennate (with the exception of the biceps brachii). By design, the total capacity for tension development is enhanced in pennate muscle by having more sarcomeres arranged in parallel and fewer in series within a given volume of muscle. In other words fibres are not orientated in true parallel to the long axis of the muscle. This can affect measurements of *in vivo* strength per anatomical mCSA in two opposing ways. Firstly, the shortening force transferred to the tendon at the muscle's insertion is less than that generated along the axis of the muscle fibres. Secondly, individual fibres do not span the whole length of the muscle, therefore anatomical mCSA will not include all fibres contributing to the force. Therefore, physiological mCSA is thought to be a better predictor of force producing capacity than anatomical mCSA. However, true physiological mCSA cannot easily be determined *in vivo* and to date there are no paediatric studies that have examined physiological mCSA.

Neuromuscular factors and strength development

Investigation into the 'quality' of children's muscle is sparse due to the methodological issues of determining neuromuscular function. Measured voluntary strength depends highly on the degree of percentage motor unit activation (%MUA). Both the level of voluntary neural drive or motor unit recruitment and the level of activation or frequency of stimulation govern %MUA. The ideal way to measure the contractile capacity of a muscle is to record the force developed during supramaximal electrical stimulation of the nerve innervating the muscle. When an electrical stimulus is applied to a motor nerve near the muscle, the resultant muscle force is free of any inhibitory influence from above the point of stimulation. On the other hand, force or torque measured during a voluntary action is the result of neuromuscular influences from the brain and inhibitory reflex influences from the spinal cord in addition to the maximum force producing capacity of the muscle. The results of tetanic electrical stimulation may not be comparable to voluntary muscle actions, since in the former method synergistic muscles may not be excited and the procedure is very painful leading to methodological, compliance and ethical issues in children.

Due to these problems with tetanic stimuli of children's muscles, most studies that have investigated maximum force producing capacity in children have used twitch stimuli because various properties of an electrically evoked twitch reveal information about intrinsic muscle properties and %MUA. Assuming that %MUA stays constant with age, then the ratio of evoked twitch force to voluntary force should stay constant with age. Based on this assumption, Davies (1985) measured both evoked twitch force and maximum voluntary force in groups of 9, 11, 14 and 21 y old males and females. The twitch torque/voluntary torque ratio of the triceps surae was similar in boys and girls aged 9 y but it gradually decreased with age in the males. However, no conclusion of a greater %MUA with increasing age in boys could be made because there was also a change in the twitch to evoked tetanus ratio with increasing age. On examination of the tetanic/voluntary ratio it appeared that %MUA may vary with age but not sex. The possibility that an inability to fully recruit the available motor unit pool may be reflected in smaller strength per mCSA scores in children than in adults has not been extensively investigated.

The interpolated twitch technique (ITT) has been used to provide an answer to the painful tetanic stimuli method and to allow %MUA to be calculated more directly. Blimkie (1989) used the ITT on maximum voluntary isometric actions of the elbow extensors and knee flexors. He found that %MUA of the knee extensors increased with age in boys from 77.7 % at 10 y to 95.3 % at 16 y, an increase in %MUA of 17.6 %. A different pattern was found for the elbow flexors whose respective values were 89.4 % and 89.9 %, indicating no change in the %MUA of elbow flexors. No studies have investigated this phenomenon in females. However, it appears that boys at least are unable to fully activate the available motor units during maximum voluntary muscle actions of the knee extensors but not the elbow flexors. In support of this others (Davies, 1985) have reported that %MUA in prepubertal boys was 78 % of the intrinsic force producing capacity during maximum voluntary knee extension. Also, the maximum rate of force production, being largely dependent on the amount and rate of neural activation has been found to be lower in children aged 8 to 11 y compared to college-age men and women.

In adults a sex difference has been demonstrated in the rate of force development which is an important quality for dynamic muscle actions in which there is limited time to generate force. Recent data examining isokinetic time to reach peak torque suggests that there are non-significant sex differences in the knee and elbow extensor and flexor muscles (Barber-Westin et al., 2005; De Ste Croix et al., 2004). In the De Ste Croix et al. (2004) study age related changes in time to peak torque were muscle group and muscle action specific leading the authors to the conclusion that care must be taken when making assumptions on differing muscle groups and muscle actions.

Time to peak twitch torque and twitch relaxation indices can be used as measure of rate of energy turnover and fibre type composition. Backman and Henriksson (1988) found that twitch relaxation times were similar in boys and girls and were not influenced by age. Also, it has been found that time to peak twitch force and relaxation times were the same regardless of age during childhood (Davies et al., 1983). Likewise, similar time to peak twitch tension was demonstrated in 3 y-olds as 25 y old adults. These data suggest that muscle fibre composition and muscle activation speed is similar between these age groups and that there is no difference in the fibre type distribution from the age of around 7 y. Previous authors have suggested that the neuromuscular system is still maturing with respect to the myelination of the nerves in younger children. Also muscle fibre conduction velocity has been seen to increase with age in children. Therefore, the influence that neuromuscular factors has on the development of muscle strength, concurrently with other know variables, remains to be established.

Conclusions

There is still a clear need for further longitudinal investigation into the static and dynamic development of muscle strength through childhood and adolescence into adulthood. Our major difficulty in describing the age and sex associated development in strength is that much of the current data reveal muscle group and muscle action specific differences in the relationships described. For example, the factors responsible for the development of isokinetic eccentric elbow flexion may be different from isometric knee extension. Despite this, the age-associated development of strength is reasonably consistent, irrespective of the muscle group or action examined. There is slight disagreement about when sex differences occur. Importantly, many of the factors discussed in this chapter play a role in strength development when examined as independent variables.

It would appear that for dynamic muscle actions in particular that mechanical factors may play a large role in the development of muscle torque and accurate investigation of the muscle moment arm, employing MRI techniques, would provide us with a clearer picture of the age and sex associated development. Our greatest challenge is to elucidate the factors that contribute to the age and sex associated development in strength concurrently with other known explanatory variables.

Future directions in paediatric strength assessment

Despite the growing number of longitudinal design research papers on the development of strength, and the use of differing methods to control for differences in body size, there are still unexplained factors that may contribute to the age and sex associated development in strength. We know relatively little about muscle fibre types in children, probably due to the invasive nature of muscle biopsies and the associated ethics that preclude the use of such techniques with paediatric subjects. There has been some tentative exploration into the use of MRI to determine fibre type (Houmard et al., 1995) but this technique has not been validated for use with children and require further investigation. Researchers are turning to new technologies to advance our understanding of the mechanisms that contribute to the development of force. For example, studies with adults have identified, using ultrasonography, muscle pennation angle (Maganaris et al., 2001). Others have begun assessing muscle tendon stiffness using ultrasonography in adult subjects (Kubo et al., 2006) but as yet there appear to be no longitudinal studies that have examined the age and sex associated changes in muscle tendon stiffness.

There is no doubt that development in techniques to measure muscle forces (eg isokinetic dynamometers), muscle size (MRI) and newer techniques for controlling for differences in body size (allometric scaling and multilevel modelling) have contributed to our greater understanding of the age and sex associated development in strength. However, there is still much we do not know and continuing advances and access to sophisticated technologies e.g. DEXA, MRI, ultrasonography, may elucidate new thoughts in this area over the coming decade.

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Key points

- The age associated development in strength is attributable to changes in growth and maturation. Sex differences appear at around 14y and very few girls out perform boys in strength tests at 18y.
- Stature and mass appear to be important explanatory variables in the development of muscle strength. PHV is a particularly important time for maximal gains in strength during childhood.
- The muscle moment arm is possibly the most important factor in the development of muscle strength with age but further longitudinal studies using MRI are needed.

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