Joint-dependence of strength and power in children and adults.

by

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Abstract

The mechanisms underlying age-related differences in maximum power production during multi-joint exercises are not fully understood. Strength and power differences between children and adults cannot be solely explained by differences in muscle size. One factor that could potentially contribute to the age-related differences in maximum power production during multi-joint exercises is a differential development of the ability to generate maximum strength and power across the involved joints. Therefore, the purpose of this study was to investigate the age-related changes in strength and maximum power at the ankle and knee joints. Electromyography of the Gastrocnemius Medialis (GM) and Vastus Lateralis (VL) muscles was recorded to test the hypothesis of muscle specificity in the levels of activation. Twenty male volunteers participated in the study. They were divided into two age groups: children (n = 10, 11.6 ± 0.8 yrs) and adults (n = 10, 27.7 ± 5 yrs). Maximal torques at 0, 30, 75 and 120 deg.s^{-1} were determined during concentric ankle plantarflexion and knee extension using a Biodex system 3 (Shirley, New York, USA). Using multivariate analyses of variance, significant age by joint interactions for both isometric peak torque and maximal instantaneous power ($p < .05$) were identified. This effect was most prominent under isometric conditions, while it was reduced under dynamic conditions. The age by joint interaction for the magnitude of muscle activity was non-significant ($p > .05$). These results do not suggest a muscle joint-specific development of the ability to recruit. However, it seems that age-related increases in muscle strength and power are joint specific. A possible explanation for the joint specific development of strength is a muscle specific development of muscle structure.

Chapter 1: General Introduction

Muscular strength is a major component of success in many sporting and day-to-day activities (Blimkie, 1989). Muscular strength increase is an important feature of growth and maturation (Froberg & Lammert, 1996). Muscle cross sectional area (CSA) increase and maturation occurrence lead to an increase in muscle strength. Similarly, the ability to generate and sustain maximum power is essential since it is required in many popular participation sports such as soccer, jumping events or rugby (Van Praagh & Doré, 2002). Since muscular strength and power are two major components affecting physical performance, the purpose of this section is to define these terms.

Strength can be defined as the peak force or torque developed during a maximal voluntary contraction (MVC) under a given set of conditions. The latter includes body position, body movement by which the force is applied, type of muscular action (isometric, concentric, eccentric, plyometric) and movement speed (Sale, 1991).

Power is expressed in Watts (W) and defined as the rate at which a mechanical work is performed under a given set of conditions (Sale, 1991; Harman, 1993). Power can also be defined as the product of force and velocity. The maximum power that human muscle can deliver is dependent on its structure, fibre type composition (Sargeant, 1994) and shortening velocity (Hill, 1938; Martin, 2007). Power can be measured in different contexts and referred as individual muscle power (Widrick, Trappe, Costill, & Fitts, 1996), individual joint power (Siegel, Gilders, Staron, & Hagerman, 2002) or overall power during multi-joint tasks such as cycling (Martin, Farrar, Wagner, & Spirduso, 2000; Korff & Jensen, 2007). A strong relationship

exists between muscle CSA and strength (Maughan, Watson, & Weir, 1983) and because muscle strength is a component of power, muscle hypertrophy also contributes to increases in power production. However, it has been reported that, changes in muscle mass do not fully account for changes in muscular power production during single joint tasks (De Ste Croix, Armstrong, Welsman, & Sharpe, 2002). De Ste Croix, Armstrong, Welsman, and Sharpe (2002), report that during a maximal isokinetic knee exercise changes in maximum power cannot only be explained by a linear increase in muscle mass in boys between 10 and 14 years of age. Changes in muscle structure could also contribute to age-related changes in maximum power production.

Age-related differences in maximum power production have also been investigated during multi-joint tasks, such as jumping or cycling. Ferretti et al., (1994) and Davies and Young (1984) compared peak power during jumping between children and adults. Both studies demonstrated that muscle mass was not the sole factor accounting for the changes in peak power. Similarly, Martin, Farrar, Wagner, and Spirduso (2000) and Doré, Diallo, França, Bedu, and Van Praagh (2000) demonstrated that differences in maximum power production, between children and adults, during short-term maximum cycling exercise cannot be fully explained by differences in muscle mass.

It becomes clear that age-related changes in maximum power production during multi-joint tasks are multifactorial. However, little is known about the relationship between the development of single joint strength and maximum power production during multi-joint tasks. The overall purpose of this thesis is to provide a first step toward a better understanding of this relationship.

Chapter 2: Literature review

An important feature of growth and maturation resides in the increase in the size and strength of skeletal muscle (Froberg & Lammert, 1996). In this section the relationship between muscle volume, or cross sectional area, and strength in adults and in children will be discussed. Since the main purpose of this dissertation was to test the hypothesis of an age by joint dependence in strength and power, the possible muscle specificity of strength development (i.e., across the knee and ankle joints) will be also discussed. Furthermore, in addition to the size of the muscle, maximum force production also depends on the degree of neural activation (Enoka, 1988; Sale, 1988). Thus the development of neural mechanisms underlying muscular force production during childhood will be discussed in this section. Finally, the importance of strength and power during multi-joint tasks will be highlighted.

Cross sectional area - strength relationship.

The measure of muscle size is a single, transverse, cross-sectional scan at right angles to the longitudinal axis of the muscle, giving the cross-sectional area (CSA) (Morse, Degens, & Jones, 2007). It is established that muscle CSA has a close relationship with muscle strength. Among the determinants of muscle intrinsic strength, preferential hypertrophy of type II fibres has been reported (Young 1984; Grindrod et al. 1987). Furthermore, in addition to its size and the extent of its neural activation, a muscle's architecture strongly influences its force production characteristics (Blazevich, 2006). Muscle architecture changes in response to different types of training (Blazevich et al, 2003; Blazevich & Sharp, 2005) and as a function of age (Binzoni et al 2001). Since skeletal muscle force production is influenced by both a muscle's size and its architecture (Kawakami, Abe, Kanehisa, & Fukunaga,

2006), these have to be considered as factors that affect torque production. A positive significant correlation between strength and cross-sectional area is reported in the literature (Maughan, Watson, & Weir, 1983). Fukunaga et al. (2001) compared elbow flexors and extensors muscle volume and torque in a cohort of trained and control participants. Muscle volume was significantly greater for elbow flexors and elbow extensors in trained participants. This increase in muscle volume led to torque differences between the two populations (i.e., 37% and 25% for elbow flexors and elbow extensors, respectively). Davies, Parker, Rutherford, and Jones (1988) found a 5.4% increase in the CSA of the elbow flexors in young participants (i.e., ranging from 19 to 33 years-old) after six weeks of isometric training. This change was accompanied by a 14.5% increase in isometric force.

Similarly, Kanehisa, Funato, Kuno, Fukunaga, and Katsuta (2003) found a 17 cm^2 increase of the quadriceps femoris CSA after a training period of 18 months in Olympic junior weightlifters. Torque values increased post-training by 21% (i.e., from 244 to 309 N.m). In a different context, Morse, Thom, Reeves, Birch, and Narici (2005) investigated the changes in CSA that occur during ageing. In this study, among 74 year-old participants, ageing-related changes (i.e., sarcopenia) were associated with a 17% and 28% decrease of the Gastrocnemius CSA and volume, respectively. These decreases were accompanied by a 40% peak torque decrement, suggesting that CSA changes affect muscle strength. Kanehisa, Ikegawa, and Fukunaga (1994) observed differences between men and women with respect of limb composition and muscle force capabilities in relation to the limb location (upper *vs.* lower extremity) and function (extension *vs.* flexion). Significant correlations between CSA and strength in all muscle groups except for the elbow extensors of the men and the elbow flexors of the women were found. In this study, men showed significantly higher

strength per unit of muscle CSA than women for the knee flexors and extensors. The authors suggested that although the difference between sexes in muscle CSA was smaller in the thigh than in the upper arm, differences in the ability to develop dynamic strength proportional to the CSA appeared mainly in the thigh muscles compared to the upper muscles. The aforementioned studies suggest that there is a relationship between muscle CSA and strength but also that this relationship may be muscle specific.

Cross sectional area - strength relationship in children.

In this section CSA – strength relationship and its underlying mechanisms (Hormones influence, Trigger hypothesis) are discussed.

In children, skeletal muscles undergo structural and functional changes (Blimkie, 1989). Fibre area increases 15 to 20 fold from birth through childhood, adolescence and young adulthood (Lexell, Sjostrom, & Nordlund, 1992). In addition, as children grow older, they acquire the ability to recruit their muscles more efficiently leading to greater strength and maximum power production (Ramsay, Blimkie, Smith, Garner, MacDougall, & Sale, 1990). It has been suggested that some of the increase in strength may be due not solely to the quantitative changes that occur while growing up but also to qualitative changes taking place simultaneously (Asmussen, 1955). These changes are influenced by children muscle mass and their ability to recruit their muscles (i.e., motor unit activation).

In adults, approximately 50% of the variance in quadriceps' strength seen between individuals can be ascribed to differences in muscle cross-sectional area (Chapman, Edwards, Greig, & Rutherford, 1984). Similarly, the increase in strength observed during childhood is likely to be attributed to increases in CSA (Parker,

Round, Sacco, & Jones, 1990). Muscle CSA increases as a function of age and lead to age-related increases in strength and considerable data support the contention that differences in muscle size account for a great proportion of differences in muscle strength during childhood (Binzoni, Bianchi, Hanquinet, Kaelin, Sayegh, Dumont, & Jequier, 2001; Kanehisa, Ikegawa, Tsunoda, & Fukunaga, 1994; Neu, Rauch, Rittweger, Manz, & Schoenau, 2002; De Ste Croix, 2007).

Ikai and Fukunaga (1968) pioneering work investigated isometric muscle strength and cross sectional area relationship among a large population (n = 245) of young participants (13-30 years). Using ultrasonography, they found a positive relationship between strength and cross-sectional area of the biceps brachii independent of age and sex (i.e., r = 0.98 and 0.91 for males and females, respectively). Others (Deighan, Armstrong, & De Ste Croix, 2002a; Deighan, Armstrong, & De Ste Croix, 2002b; Round, Jones, Honour, & Nevill, 1999) reported a positive correlation between muscle size and isometric strength (r = 0.87), isokinetic knee strength (r = 0.73), isokinetic elbow strength (r = 0.82) and isokinetic triceps surae strength (r = 0.91). Tanner, Hughes, and Whitehouse (1981), found that from 3 to 18 years of age arm muscle width increased by approximately 50% in boys, indicating increases in CSA of 125%. Furthermore, Parker, Round, Sacco, and Jones (1990) found that elbow flexor strength increased by 95% in boys from 12 to 18 years of age suggesting that changes in the size of muscle mainly account for the increases in strength. Kanehisa, Ikegawa, Tsunoda, and Fukunaga (1994) investigated the relationship between age and CSA of limbs during growth and middle age. The major finding of this study was a muscle CSA increase with growth, from the age of 6 years to 17 years. Similar findings were reported by Wood, Dixon, Grant, and Armstrong (2004) who found a concomitant increase in strength and cross sectional area. The

authors observed a 30% increase in isometric elbow extension strength between 13 and 15 year-old children. This increase was accompanied by a 19% increase in CSA. The same trend was observed for the elbow flexors muscles (i.e., a 26% increase in isometric torque with an 18% increase in CSA). Recently, Wood, Dixon, Grant, and Armstrong (2006) found that elbow flexor CSA was proportional to isometric torque and explained 47 to 57% of the torque variance across the whole joint range of motion in prepubertal children (i.e., 9.6 year-old)

The above-cited studies support the contention of a relationship between muscle strength and CSA. However, it has been reported that strength and power differences between children and adults cannot be solely explained by differences in muscle size (Martin, Farrar, Wagner, & Spirduso, 2000; De Ste Croix, Armstrong, Welsman, & Sharpe, 2002). That is, a muscle's specificity in the development of strength and power may be another contributor of the age-related differences in strength during static and dynamic tasks.

Strength and hormones

In this sub-section, the role of hormones that are the most involved in growth and which have a direct relationship with strength enhancement will be discussed. Growth hormone, or somatotropin, is essential for normal growth. Its effects are both direct and indirect. Direct effects reflect the metabolic role of growth hormone on carbohydrate and fat metabolism. Indirect effects of growth hormone on somatic growth are mediated by the somatomedins. Somatomedins are growth-promoting substances produced in the liver in response to stimulation by growth hormone (Malina and Bouchard, 1991). Somatomedins stimulate protein synthesis and increase cell proliferation resulting in tissue growth (i.e., anabolism).

There is also evidence to demonstrate the association between testosterone and strength development during puberty. Increase in circulating testosterone levels seems to be primarily responsible for the acceleration in muscle mass and strength in males at puberty (Rowland, 1996). Parker, Round, Sacco and Jones (1990) measured the isometric strength of forearm flexor and knee extensor muscles in boys and girls between the ages of 8 - 18 years and showed that, in the older children, whilst boys were stronger than girls in both muscle groups, the boys had proportionally greater strength in the upper arms. It seems likely that these differences in muscle development are due to the increase in circulating testosterone which is a feature of maturation in normal male adolescents at this time (Winter and Faiman 1972, Sizonenko and Paunier 1975). Similarly, Round et al. (1999) found that testosterone levels could explain most of the gender difference in maximal isometric biceps force during puberty. Testosterone stimulates anabolic processes in skeletal muscle and appears to be the principal hormone responsible for the development of strength.

The thyroid gland also plays an important role in growth and maturation. The thyroid gland is sometimes referred as the great metabolic gland of the body (Malina and Bouchard, 1991). The major effect of thyroid hormones on the body is a general increase in oxygen consumption in most tissues (e.g., skeletal muscle, heart). Another important hormone, insulin, has a major role in growth and maturation. It is essential in carbohydrate metabolism. Insulin enhances the rate of glucose metabolism by stimulating the transport of glucose and amino acids through cell membranes, and is also known to be a powerful anabolic agent.

Trigger hypothesis

The effects of puberty have been studied to further investigate the relationship between muscle CSA and force production (Neu et al. 2002). It seems that prepubescent children do not respond to a training regimen as well as post pubescent children (Bar-Or, 1989). The low growth hormone levels before the onset of puberty (Martha et al, 1989) may be responsible for this phenomenon. Differences in exercise-induced changes in cardiovascular function between pre- and post pubescent children are explained in terms of a "trigger hypothesis." This hypothesis predicts that before puberty there will be only small training-induced biological alterations because of the lack of hormonal stimulus. Based on the trigger hypothesis it is suggested that emphasis should be placed on skill acquisition rather than physiological conditioning during prepuberty (Katch, 1983). Nevertheless, it has to be noted that the trigger hypothesis was posed to test for physiological differences in children (i.e., aerobic potential). In their meta-analysis, Payne and Morrow (1993) found that reported changes (i.e., effect sizes) in VO_{2max} in children are small to moderate and are a function of the experimental design used. However, training-induced changes in muscular strength or endurance have been found in prepubescent children. For instance, Sailors & Berg (1987) found that gains in prepubescence are similar to those seen in pubescent and post pubescent children. Furthermore, strength training effects have been investigated among prepubescent boys ranging from 9 to 11 years of age (Ramsay et al, 1990). Following a 20 week training programme, an increase in 1 repetition maximum bench press, leg press exercises and also in isometric elbow flexion and knee extension strength were reported. From the aforementioned, it seems that the trigger hypothesis may not be transferable to adaptations related to strength, an observation that deserves further study.

Allometric scaling.

In this section, the principle of allometric scaling will be defined. Allometry is a method of mathematically expressing the extent to which a variable is related to a unit of body size, usually body mass, as size increases (Rowland, 1996). When conducting research on the development of strength, the researcher often faces the challenge of finding a meaningful measure to normalise forces or torques according to differences in size. In children, changes in strength can be confounded by changes in overall dimensions. While changes in strength may be induced by a training program, they may also simply result from growth. That is why, when testing children of different ages, assessing the effects of an intervention can only be achieved if the effects of growth are accounted for by normalisation. Because maximum torques at the hip, knee, and ankle do not scale geometrically with body mass, simple mass normalisation may not be appropriate for cross-sectional or longitudinal comparisons of strength in children. As an alternative, allometric scaling has been widely recommended and is based on the principle of geometric similarity (Jaric, 2002). It is worth noting that most of the arguments for and against normalisation methods used in the literature have been based on allometric scaling assuming the principle of geometric similarity. However, it is known that human bodies are neither similar in shape nor in body composition. Allometric scaling has the advantage of not assuming a specific a priori relationship between strength measures and measures of body size (e.g., mass, body mass index; Wren and Engsberg, 2007). In the present study the variable of interest was muscle strength and could be modelled as a general function of a confounding variable, for example, body mass (m), using the following equation:

$$\mathbf{Sn = S/m^{b}}$$

where Sn is the normalized strength and b is the allometric scaling parameter (Jaric, 2002). The exponent b can be determined through theoretical analysis. In this case, geometric similarity is usually assumed, with muscle force being proportional either to body height squared (H^2) or to body mass to the power of two-thirds ($m^{2/3}$). That is, to obtain an index of muscle strength independent of body size, the recorded strength should be divided by any body length (e.g. body height) squared, or any specific area (e.g. muscle CSA) or body mass to the power of two-thirds (Jaric, 2002). Under the geometric similarity assumption, the scaling parameter would be b equal to 1.0 for muscle torque and b equal to .67 for muscle force (Jaric, 2002).

Muscle specificity of strength development.

In addition to a muscle's CSA, a muscle-specific development of strength may be a factor that leads to changes in force production between children and adults. For instance, Asmussen and Heebøll-Nielsen (1955) investigated muscular strength of the leg extensors, elbow flexors and finger flexors in 200 male children ranging from 7 to 17 years of age. The authors found that the increase in muscular strength was different between the three muscle groups tested (i.e., 42; 33; 30% increase for the leg extensors, elbow flexors and finger flexors, respectively). Asmussen and Heebøll-Nielsen suggested that in addition to quantitative changes (i.e., size of the muscle), qualitative changes may have occurred. That is, changes in muscle fibre type or an increased ability to voluntarily mobilise the muscle may have played an important role in strength enhancement. From the observation of differences in muscular strength found among different muscle groups the authors speculated that the leg muscles could develop more rapidly than the other muscles tested (i.e., finger flexors and elbow flexors). Data from different muscle groups have been reported by

Sunnegardh, Bratteby, Nordesjo, and Nordgren (1988). These authors studied the isometric and isokinetic muscle strength in 8 and 13 year old children (girls and boys). Knee, handgrip, and trunk flexion and extension strength was assessed. Knee strength was also recorded isokinetically at 12, 90 and 150 deg.s^{-1}. Firstly, strength variables were, in general, found to be very similar in the 8 year old boys and girls. However, by the age of 13, the boys were stronger than the girls. Secondly, knee strength increased by 60% at every speed tested (0, 12, 90 and 150 deg.s^{-1}) with increasing age Similarly, handgrip strength was 58% greater in 13 year-old children than in 8 year-old children. However, the age-related increases observed in trunk flexion and extensions were somewhat lower at 52 and 47%, respectively. These results are in agreement with Asmussen and Heebøll-Nielsen (1955) who suggested that the age-related changes in strength may be muscle specific. The similarity observed between knee and handgrip strength may be explained by older children's increased ability to recruit these muscles. Furthermore, Kanehisa, Ikegawa, Tsunoda, and Fukunaga (1995) observed differences in strength between the flexors and extensors of both the knee and elbow. As an explanation of the differences of this increase in strength between muscle groups, a muscle-specific growth of CSA, the degree of maturation of the nervous system and the development of the neuromuscular coordination in a specific muscle group have been hypothesised (Kanehisa, Ikegawa, Tsunoda, & Fukunaga, 1995).

In an extensive review, Blimkie (1989) suggested that the increase in muscle mass and the percentage change in force during childhood may vary from muscle to muscle. Support for the hypothesis regarding a muscle specific development of strength comes from different studies. In a cross sectional survey investigating upper and lower limb strength, Parker, Round, Sacco, and Jones (1990) found a 79%

increase in quadriceps and a 73% increase in elbow flexors strengths in children aged between 5 and 18 year-old. De Ste Croix, Deighan, and Armstrong (2004) investigated muscle strength across different joints (knee and elbow) during isokinetic actions among 9-10 year-old boys, 16-17 year-old boys and adult participants Their results revealed that age-related changes in the time to peak torque were muscle group and muscle action specific. In a different context, results from Lanza, Towse, Caldwell, Wigmore, and Kent-Braun (2003) study suggest that the effects of age on the torque-velocity and power-velocity relationships of the ankle dorsiflexors (DF) and knee extensors (KE) may be joint specific. Lanza, Towse, Caldwell, Wigmore, and Kent-Braun (2003) investigated the effects of age on muscle torque and power in two muscle groups among 12 young (26 ± 5 yr) and 12 older (72 ± 6 yr) healthy adults during maximal voluntary concentric contractions. The authors compared the torque responses for the DF and KE and observed a greater decrement with age for the KE (36% less torque for the older participants at 270 $deg.s^{-1}$) than the DF (16% less at 120 $deg.s^{-1}$). Lanza, Towse, Caldwell, Wigmore, and Kent-Braun (2003) suggested that the muscle specificity found in their study could be explained by the quantity and quality of muscular activation. From the aforementioned, it becomes clear that age related changes in strength are cross sectional area dependent but may be joint specific as well. Power production across different joints in cycling and jumping activities has been shown to be a major factor determining the performance. During dynamic movements, maximum overall power production requires maximum power production at the individual joints (Hubley & Wells, 1983). Consequently, it is important to understand if the increase in maximum power production during childhood is joint-dependent. De Ste Croix, Deighan, & Armstrong (2004) investigated muscle contractile properties across different joints (knee and elbow)

during isokinetic actions. Their results revealed that age-related changes in the time to peak torque appeared to be muscle group and muscle action specific. A possible explanation of this phenomenon could be a difference of maximum power across the lower-limb joints (Korff & Jensen, 2007). The study demonstrated that, while cycling, children exhibited a smaller relative maximum muscular power at the hip joint, whereas the knee and ankle power were similar. However, the hypothesis of a joint-dependence of maximum power output was not tested and the exercise was performed at sub-maximal intensities. Therefore, answering the question regarding a possible joint dependence in strength and power in children will provide further insights to the existing literature.

Magnitude of muscle activity and strength.

Because of the relationship between muscle size and strength, it is to be expected that an increase in muscle mass will be the main contributor of an increase in muscle strength. However, in addition to the size of the muscle, maximum force production also depends on the degree of neural activation (Enoka, 1988; Sale, 1988).

A muscle's force output can be modulated over an enormous range. This modulation is accomplished by the recruitment of motor units (Clamann, 1993). It is well know that the central nervous system (CNS) controls two parameters of motor unit activation to produce a desired force output: the number of recruited motor units and their firing rate (Erim, De Luca, Mineo, & Aoki, 1996). The CNS triggers action potentials along a motor axon and across the neuromuscular synapse at all its muscle fibres. Most muscle contractions are evoked by trains of repetitive action potentials. In the case of a high level of force required, the action potential rate is increased and the twitches summate until peak force is reached (Kernel, 2003).

Following strength training programmes increases in maximal torque and muscle CSA have been reported in adults (Garfinkel & Cafarelli, 1992; Narici, Hoppeler, Kayser, Landoni, Claassen, Gavardi, Conti, & Cerretelli, 1996). However, it is difficult to attribute all of the relatively large increases in torque to muscle hypertrophy at the onset of a training programme. Early increases in muscular strength after a training intervention are often attributed to neural factors (Moritani & DeVries, 1979; Del Balso & Cafarelli, 2007).

During exercises such as running or cycling, a synergistic activity is developed between the lower limb muscle groups, and muscular adaptations are developed between agonist and antagonist muscles, and between synergistic muscles (flexors or extensors) (Moritani, 1993). Thus, muscular performance is not only dictated by a muscle's size but also by the nervous system's ability to activate it (Sale, 1988).

In children, although increases in muscular strength are closely related to changes in muscle CSA, strength enhancement can also be explained by an increase in their capacity to recruit their muscles. In a study aiming for identifying the development of arm and thigh muscles in relation to muscle size during adolescence, results showed evidence that prepubertal children do not develop strength in proportion to their muscle CSA (Kanehisa, Ikegawa, Tsunoda, & Fukunaga, 1995). Since previous findings suggested that preadolescent children do not fully activate their motor units during voluntary maximum muscle actions, Kanehisa, Ikegawa, Tsunoda, and Fukunaga (1995) pointed out that the absence of proportionality between muscle CSA and strength might be due to children's lack of ability to mobilize their muscles voluntarily. In another context, results from Jubrias, Odderson, Esselman, and Conley (1997) showed that the decline in force with age was not only due to a decrease in CSA but also to changes in magnitude of muscle activity and

contractile function. As mentioned earlier, strength is one of the basic determinants of performance and most of the studies have focused on changes in isometric strength or on the strength-muscle size relationship. Nevertheless, in addition to its mass, a muscle's activity is another important determinant of muscles' performance. Among 6-year-old children, Asai and Aoki (1996) found that children's electromechanical delay was greater than their adult counterparts. Lambertz, Mora, Grosset, and Perot, (2003) found that triceps surae activation required to maintain a level of torque was higher in the 7-year-old children compared with the 10 year-old ones. These findings suggest that muscle recruitment patterns are age-dependent. It seems that children do not activate all of their motor units.

Maximum power during multi-joint tasks.

In children, peak muscle power during jumping is known to be lower than in adults (Davies, Barnes, & Godfrey, 1972; Moritani, Oddsson, Thorstensson & Astrand, 1989). Since muscle CSA is smaller in children than in adults (Ikai & Fukunaga, 1968), changes in power production may result from relative differences in muscle mass. However, changes in muscle size account only partially for changes in muscle peak power (Ferretti, Narici, Binzoni, Gariod, Le Bas, Reutenauer, & Cerretelli, 1994; Grassi, Cerretelli, Narici, & Marconi, 1991; Martin, Farrar, Wagner, & Spirduso, 2000; Mercier, Mercier, Granier, Le Gallais & Prefaut, 1992). Ferretti et al., (1994) investigated peak jumping power changes in children aged 8 to 13 years. Compared to an adult group aged 20 to 35 years, peak power values were 65% lower in children. In addition, muscle CSA was found to be 45% less in children than in adults. Ferretti et al., (1994) concluded that the changes observed in peak power were only partially accounted for by changes in muscle CSA. Similarly, Mercier, Mercier,

Granier, Le Gallais, & Prefaut, (1992) found greater differences in power, as measured by a force-velocity test, than in muscle mass. The authors investigated sixty-nine young boys aged 11 to 19 years and found an increase in maximal power even when the latter was corrected for lean body mass. Thus, it seems that factors other than muscle size contribute to power production and affect maximum power production during multi-joint exercises in children.

Power production across different joints in cycling and jumping activities has been shown to be a major factor determining performance. During dynamic movements, maximum overall power production requires maximum power production at the individual joints (Hubley & Wells, 1983). It also requires the performer to have an optimal intermuscular coordination leading to a greater force production (Sale, 1988). Consequently, it is important to understand if the increase in maximum power production during childhood is joint-dependent. De Ste Croix, Deighan, & Armstrong (2004) investigated muscle contractile properties across different joints (knee and elbow) during isokinetic actions. Their results revealed that age-related changes in the time to peak torque appeared to be muscle group and muscle action specific. A possible explanation for this phenomenon could be a difference of maximum power across the lower-limb joints (Korff & Jensen, 2007). The study demonstrated that, while cycling, children exhibited a smaller relative maximum muscular power at the hip joint, whereas the knee and ankle power were similar. However, the hypothesis of a joint-dependent maximum power output was not tested, and the exercise was performed at sub-maximal intensities.

Doré, Diallo, França, Bedu, and Van Praagh (2000) observed a significantly higher lean leg volume/body mass ratio in adults than in children. Consistent with this, data from Ferretti, Gussoni, Di Prampero, and Cerretelli (1987) showed an

increase of muscle mass normalised for total body mass from 42 to 54% in children aged from 5 to 18 years. It has been shown that, when scaled to muscle size, the power of adults was 20-53% greater than the one of children, suggesting that additional factors may play a role in the age-related changes in power production (Blimkie, Roache, Hay, & Bar-Or, 1988). In a developmental context, a differential development of maximum force and power production across the lower limb joints could lead to different coordination patterns and has thus a potential effect on maximum power production during multi-joint exercises.

Chapter 3: Study

Introduction.

Children's skeletal muscles undergo structural and functional changes due to neuronal, hormonal and biomechanical factors (Blimkie, 1989). As a result, the ability to produce a maximum force or power during exercise increases as a function of age (Van Praagh & Doré, 2002). It has been reported that strength and power differences between children and adults cannot be solely explained by differences in muscle size (Martin, Farrar, Wagner, & Spirduso, 2000; De Ste Croix, Armstrong, Welsman, & Sharpe, 2002). De Ste Croix, Armstrong, Welsman, and Sharpe (2002) reported that during a maximal isokinetic single-joint knee exercise not all age-related changes in maximum power can be explained by an increase in muscle mass in boys between 10 and 14 years of age. Age-related differences in maximum power production have also been investigated during multi-joint tasks. Ferreti et al., (1994) and Davies and Young (1984) compared peak power during vertical jumping between pre-adolescent children and adults. Both studies demonstrated that a large part of the observed difference in peak power could not be explained by differences in muscle mass. Similarly, Martin, Farrar, Wagner, and Spirduso (2000) and Doré, Diallo, França, Bedu, and Van Praagh (2000) showed that differences in maximum power production during a short bout of maximum cycling between children and adults cannot be fully explained by differences in muscle mass.

One factor that could potentially contribute to the age-related differences in maximum power production during multi-joint exercises is a differential development of the ability to generate maximum strength and power across the involved joints (De Ste Croix, Deighan, & Armstrong, 2004; Korff & Jensen, 2007).

Power production across different joints in cycling and jumping activities has been shown to be a major factor influencing performance, as during dynamic movements, maximum overall power production requires maximum power production at the individual joints (Hubley & Wells, 1983). Jumping is an explosive movement that requires strength and power, especially from the extensor muscles of the lower extremities (Asley & Weiss, 1994; Bosco, 1981; Hubley & Wells, 1983). Support for the hypothesis that the development of strength and power during childhood may be joint specific comes from De Ste Croix, Deighan, and Armstrong (2004). These authors investigated muscle contractile properties across different joints (knee and elbow) during isokinetic actions among 9-10 year-old boys, 16-17 year-old boys and adult participants. Their results revealed that age-related changes in the time to peak torque were muscle group and muscle action specific. Furthermore, Korff and Jensen (2007) showed a joint-specific development of peak power production during sub-maximal cycling in children between 5 and 10 years of age. Their study was designed to determine age-related changes in intermuscular synergies during a submaximal exercise and did not specifically test the joint-dependence of peak power production during maximal exercises. Consequently, the question about a differential development of joint strength and power production remains unanswered. Therefore, the first purpose of this study was to determine the joint dependence of age-related changes in maximum force and power production at different velocities. It was hypothesised that age-related changes in maximum force and power production differ across the ankle and knee joints.

A possible contributor to the differences in power production across the lower-limb joints could be a differential ability in children to activate their muscles. It is known that in addition to the size of the muscle, maximum force production also

depends on the degree of neural activation (Enoka, 1988; Sale, 1988). The changes in the magnitude of muscle activity may involve enhanced motor unit recruitment, an increased firing rate of activated motor units, or a change in motor unit firing rate (Duchateau & Enoka, 2002; Enoka & Stuart, 1985). In children, it has been suggested that the non-proportional relationship between strength and muscle size might be due to children's inability to optimally mobilize their muscles voluntarily (Kanehisa, Ikegawa, Tsunoda, & Fukunaga, 1995). Paasuke, Ereline, and Gapeyeva (2000) observed a greater ratio between peak torque and the magnitude of muscular activation in 11 year-old children when compared to adolescents and adults. All these findings suggest that children's ability to recruit their motor units' increases with increasing age. In the context of this investigation, it would be of interest if the hypothesised joint specific development of maximum strength and power would be accompanied by a differential development of the ability to recruit the involved muscle group. Therefore, the second purpose of this study was to test the hypothesis that a possible age by joint interaction in peak torques would be accompanied by muscle-specific differences in the levels of activation.

Methods.

Participants.

Twenty male volunteers participated in the study. They were divided into two age groups: children (n = 10, 11.6 ± 0.8 yrs) and adults (n = 10, 27.7 ± 5.0 yrs). The study protocol complied with the Helsinki declaration for human experimentation. All the experimental procedures used in this study were approved by the Ethics Committee of the School of Sport and Education at Brunel University. Possible risks

and benefits were explained and written informed consent was obtained from all participants. Verbal assent from the child was obtained prior to the obtaining of written informed consent from the parents. None of the participants suffered from muscle soreness, joint injury, or peripheral vascular disorder. Adult participants were all fully familiar with laboratory exercise testing procedures. Prior to the testing procedures care was taken to familiarise the children with the laboratory environment. That is, a detailed explanation of the protocol and devices used was undertaken.

Experimental protocol.

The participants came to the laboratory on one occasion. They had been instructed to arrive at the laboratory in a rested state and to avoid strenuous exercise in the 48 hours preceding a test session. Participants were also asked to avoid caffeine intake within the 8 hours preceding the tests. For all the participants, tests took place at the same time of day (between 10.30am and 3.00 pm) to minimise the time of day effect on maximal force (Martin, Carpentier, Guissard, van Hoecke, & Duchateau, 1999). Temperature in the laboratory remained constant (20.4 ± 0.3° C) due to its effect on muscle force generation and rate processes (i.e., maximal velocity of shortening and power output) (Bennett, 1984; Kawai, 2003).

Positioning of the participants.

Ankle tests:

Participants were placed in the positioning seat with the knee extended. The relative hip angle between trunk and thigh was 85°. The foot was attached to the adapter after adjustment of the height of the dynamometer and the length of the seat,

allowing the axis of the rotation of the dynamometer to be aligned with the lateral malleolus. The test began with dorsiflexion from the neutral position of the ankle.

Knee tests:

Participants were placed in the positioning seat with the hip at an angle of 85° of flexion. The participant was strapped in position after adjustment of the depth of the seat. The lateral epicondyle of the knee was aligned with the axis of rotation of the dynamometer lever arm.

Gravity correction was performed at the same angle for each joint and at each velocity tested.

Strength assessment.

The maximal torques from the isokinetic tests were determined during concentric ankle plantarflexion and knee extension using a Biodex system 3 (Shirley, New York, USA) which was calibrated before the beginning of the study. The order of joint to be tested and the isokinetic speeds were randomised. A standardised warm-up/familiarisation session was performed as follows: first, participants performed a two minute cycling exercise at 60 rpm (60 and 30 watts for the adults and children, respectively). Then, they were asked to perform a pre-conditioning exercise consisting of four ramped isometric ankle plantarflexion/dorsiflexion and knee extension/flexion (they were instructed to gradually increase the force until they reached what they perceived to be 80% of their maximum). This was followed by three 3 s isometric maximal voluntary contractions (IMVC) separated by 40 seconds of recovery. The IMVCs were performed at (i) 70° for the knee test (0° corresponded to the knee fully

extended) and (ii) 90° for the ankle test (neutral position, foot perpendicular to the tibia). The IMVC values were then averaged. The participants were asked to do the IMVC before each isokinetic test. This procedure was followed for both the ankle and knee joints.

Then, as a familiarisation session to the isokinetic assessment, participants were asked to do six submaximal trials followed by two efforts performed close to their maximum (Brown & Weir, 2001; De Ste Croix, Deighan, & Armstrong, 2003). Participants were asked to perform five isokinetic concentric tests at three different velocities (30, 75 and 120 deg.s^{-1}). Resting times were approximately 80 s and 10 min between the velocities and the joints tested, respectively. Verbal encouragement was given during the tests. Participants were strapped with two chest straps, a hip strap and a thigh strap. Care was taken to not over tighten the straps in order to avoid any pain or ischemia. After positioning the participants, the ranges of movement were determined for each joint. The recovery periods mentioned in this experimental set-up were used in order to avoid any fatigue effect or muscle soreness, following the procedure recommended by the American Society of Exercise Physiologists (Brown & Weir, 2001).

Muscle activity.

Surface EMG from the muscle belly of the Gastrocnemius Medialis and Vastus Lateralis were recorded during the exercises. We used 28-mm-diameter skin-surface electrodes (Arbo Infant Electrodes, Tyco Healthcare, Neustadt Donau, Germany). Two electrodes were placed over the belly of each muscle and secured with tape (3M, Tegaderm, Neuss, Germany). Electrode placement was carried out in

accordance with the Surface EMG for Non-invasive Assessment of Muscles (SENIAM) recommendations (Hermens et al, 1999).

The ground electrode was placed on the wrist or the right malleolus for the knee and ankle tests, respectively. Low impedance at the skin-electrode surface (< 5 kΩ) was obtained by shaving and cleaning the skin with alcohol. EMG signals were collected through an amplifier (model 1902, Cambridge Electronic Design, Cambridge, UK), band-pass filtered at 10-350Hz and sampled at 1000Hz using an analog-to-digital converter (micro 1401 mkII, Cambridge Electronic Design), and acquired on a personal computer running commercially available software (Spike 2 version 5.14, Cambridge Electronic Design). The EMG signal was analysed in the time domain, as root mean square (RMS) amplitude with a time constant of 25 ms (Ross, Middleton, Shave, George & Nowicky, 2007). RMS values (in mV) were calculated for each muscle on a burst by burst basis (See fig. 1). Burst onsets and offsets were determined from baseline EMG signals (i.e, ~ 5s window) using a constant electric threshold of ± 0.2 mV (Billaut, Basset, & Falgairette, 2005).

Figure 1. Torque and EMG traces for a representative participant during IMVC of the knee joint. RMS values were calculated on a burst by burst basis (EMG burst onset and offset are delimited by cursors 1 and 2, respectively).

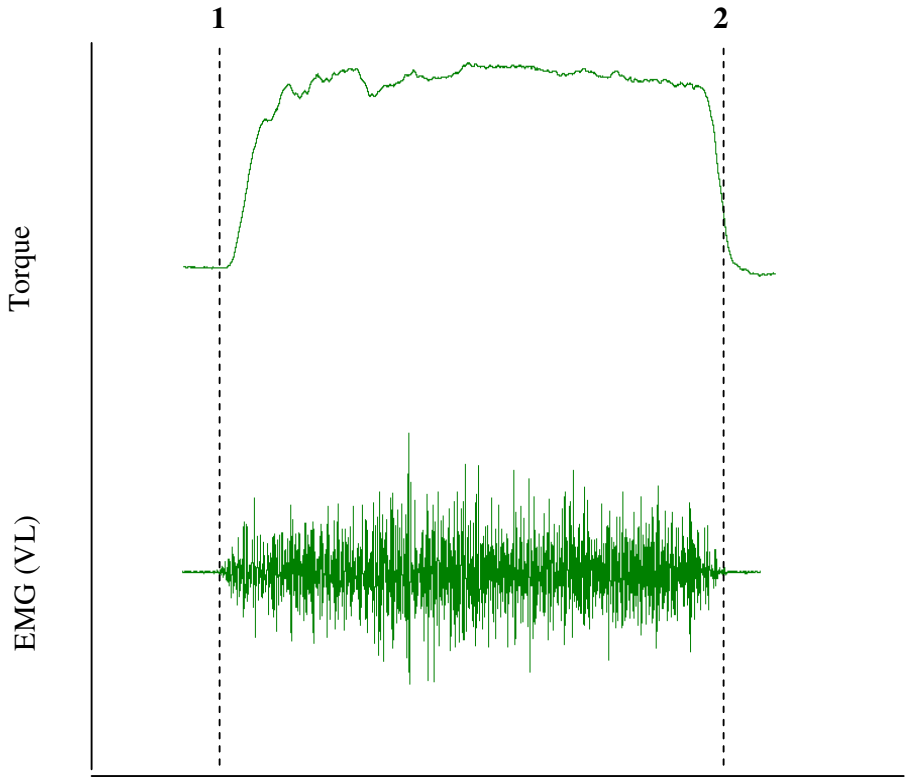


Figure 2. Participant positioned in the isokinetic dynamometer.

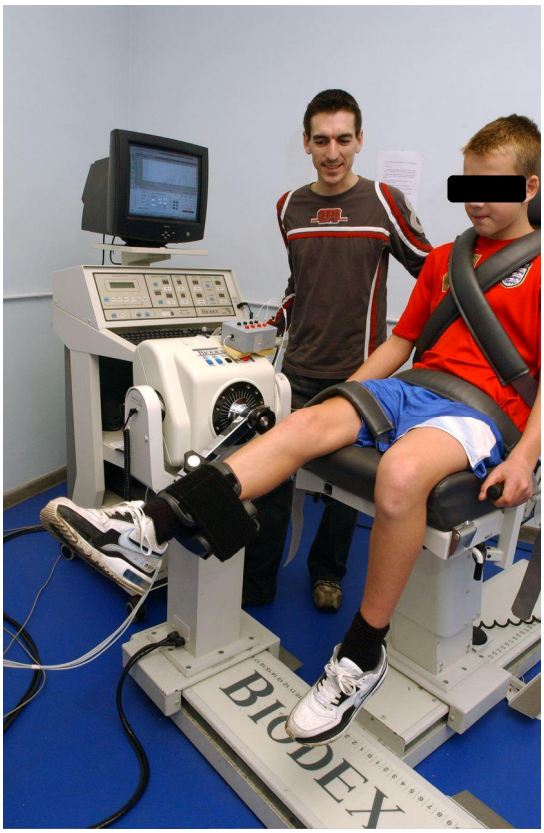


Table 1. Group characteristics of the participants: means ± standard deviations are presented
for age, stature, and body mass.

	N	Age (years)	Stature (cm)	Mass (kg)
		Mean ± SD		
CH	10	11.6 ± 0.8	148.35 ± 10.31	42.64 ± 11.7
AD	10	27.7 ± 5	176.82 ± 7.16	78.68 ± 13.57

Statistical analysis.

One of the assumptions of the MANOVA is that there should not be a difference in the covariance of the dependent variables across the groups. Prior to performing a MANOVA, the homogeneity of covariance assumption was assessed. This assumption was checked by the Box's test of equality of covariance (Hinton, Brownlow, McMurray and Cozens, 2004). As can be seen below the homogeneity of covariance assumption was met as the box's test was not significant ($p = 0.07$).

Box's Test of Equality of Covariance Matrices

Box's M	98.997
F	1.378
df1	36
df2	1090.213
Sig.	.070

In order to test the joint-dependence of the age-related changes in power and strength an age by joint MANOVA with repeated measures was performed. Dependent variables were peak torques at 0, 30, 75, and 120 $deg.s^{-1}$. In case of the age by joint interaction being significant, follow up ANOVAs were performed for each dependent variable. Effect sizes for each dependent variable were calculated by dividing the difference in group means by the pooled standard deviation. We used effect sizes to interpret the difference in maximum torques, magnitude of muscle activity between ankle and knee joints within each group (e.g., Ankle *vs.* Knee in children).

To interpret the effect sizes Cohen's (1988) classification scheme was used. According to Cohen (1988), effect sizes smaller than 0.5 are interpreted as a small

effect. Effect sizes greater than 0.5 and smaller than 0.8 are interpreted as a moderate effect. Effect sizes greater than 0.8 are interpreted as a large effect.

To test the joint dependence of the age-related changes in the magnitude of muscle activity, an age by muscle (i.e., GM and VL) MANOVA with repeated measures has been performed. The dependent variable was RMS at different velocities and was normalised to the highest value among the four velocities. To ensure the robustness of our results, we performed the statistical analyses using different normalisation techniques (See appendix A). We applied four different normalisation techniques. These were A, B, C and D. The age by joint interaction for the magnitude of EMG was independent of the normalisation technique (See Appendix A for details).

Due to time constraints of some children participants, we were only able to collect EMG data for 8 children. As a result, the EMG data analysis is representative of 16 participants (i.e., 8 children *vs.* 8 adults). For all statistical tests, the type I error was set to .05.

Results.

We found a significant interaction regarding the age-related joint dependence in strength (Figure 3). The MANOVA revealed that the hypothesised age by joint interaction in peak torques was significant ($p < .05$; Wilk's Lambda = 0.260, $F(18, 1) = 10.67$, $p < .001$).

Follow up ANOVAs revealed that the effect of age on strength and power at the ankle and knee joints was significant at 0 ($F(18, 1) = 36.61$, $p < .001$), 30 ($F(18, 1) = 5.2$, $p < .05$), 75 ($F(18, 1) = 7.3$, $p < .05$) and 120 ($F(18, 1) = 13.4$, $p < .05$) $deg.s^{-1}$ (Figure 3). In spite of the significant interactions for all conditions, the effect

sizes revealed that the age x joint interaction in peak torques was most pronounced under isometric conditions. Under isometric conditions, the effect size describing the difference between the ankle and the knee joints was moderate in children while the equivalent effect size was large in adults (Table 2). Under isokinetic conditions the effect sizes describing the difference between the ankle and knee joints were large and similar in magnitude for both children and adults (Table 2). When normalised to body mass, no significant interaction was found ($p > .05$; Wilk's Lambda = 0.639, $F(18, 1) = 2.11$, $p > .05$). These data are presented in the thesis' appendix (Pages 57-58). Changes of within group variability (i.e., coefficient of variance) are presented when torque was normalised and not normalised to body weight. The normalised torque data are not included here since the isokinetic exercises performed in this study were non-weight bearing activities. Furthermore, the present study was not investigating absolute differences in strength but Age x Joint interactions. Additionally, no evidence has been provided to show that this normalisation process is effective in eliminating the influence of size as a confounding factor in the analysis (Wren and Engsberg, 2007). Also, as maximum torques at the knee and ankle do not scale geometrically with body mass, simple mass normalization may not be an appropriate measure for comparisons of strength in children.

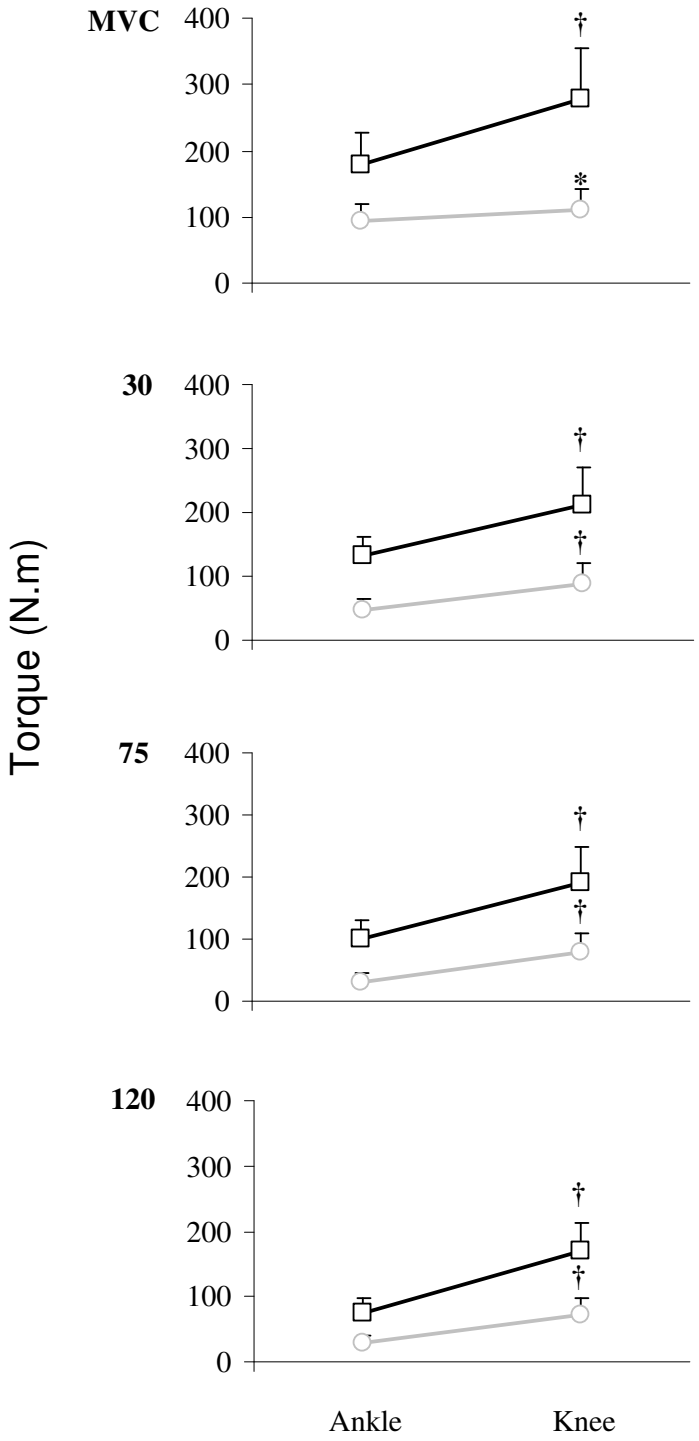
Finally, it is worth noting that the statistical power decreased when normalising to body weight, from 99 to 48%.

In contrast to the second hypothesis, the age by joint interaction for the magnitude of muscle activity was non-significant (Wilk's Lambda = 0.655, $F(14, 1) = 1.45$, $p > .05$).

Table 2. Effect sizes describing pairwise joint differences in maximum joint torques (*CH*
children, *AD* adults).

Comparison	Speeds ($deg.s^{-1}$)			
	0	30	75	120
Ankle-Knee (CH)	0.58	1.29	1.45	1.45
Ankle-Knee (AD)	1.25	1.28	1.49	1.62

Figure 3. Maximal torque values for children (—○—) and adults (—□—) across the ankle and knee joints. Values are plotted during MVC and at 30, 75 and 120 deg.s^{-1}. The symbol † indicates a large effect in torque values between the ankle and knee joints. The symbol * indicates a moderate effect. Means and standard deviations are plotted for adults and children (n = 10).



Discussion.

The purpose of this study was to determine the joint dependence of maximum force and power production at different velocities. Our hypothesis was to test if children muscular strength and power were joint dependent. In conformity with our hypothesis, we demonstrated that age-related differences in peak torque production were joint-dependent. While the age by joint interaction was significant at all movement speeds, the analysis of the effect sizes revealed that the age effects were only joint dependent during isometric conditions. Under isometric conditions children's peak torque at the knee joint was only moderately greater than that at the ankle joint. In adults, this effect was large. Children seemed to not be able to produce a greater torque at the knee joint than at the ankle joint under isometric conditions. This let us speculate that children took advantage of the stretch and shortening cycle and had a similar pattern as their adults' counterparts during dynamic movements (i.e., greater torque at the knee joint than at the ankle joint). Our results support the notion of a muscle-specific development of growth on the development of strength and power for specific muscle groups. Asmussen and Heebøll-Nielsen (1955) demonstrated that the development of strength of the leg extensors, elbow flexors and finger flexors in children ranging from 7 to 17 year-old is muscle-specific. De Ste Croix, Deighan, and Armstrong (2004) demonstrated that age-related changes in time to peak torque are muscle group and muscle action specific (i.e., extensors and flexors of the elbow and knee joints). Similar results from a study comparing young and older adults suggest that the effects of age on the torque-velocity and power-velocity relationships of the ankle dorsiflexors (DF) and knee extensors (KE) may be joint specific (Lanza, Towse, Caldwell, Wigmore, and Kent-Braun, 2003).

Investigating the ankle and knee joints is important since they are involved in many sports and daily living activities. Moreover, their contribution to tasks such as jumping is a major component of the performance. Our results suggest that knee and ankle maximum power is independent of joint and might not influence overall power production during multi-joint tasks. Our study was motivated by the notion that a differential development of lower limb joint power production could contribute to differences in overall power during multi-joint tasks. Power production across different joints in cycling and jumping activities has been shown to be a major factor influencing performance, as during dynamic movements, maximum overall power production requires maximum power production at the individual joints (Hubley & Wells, 1983). It has been reported that age-related differences in overall maximum power during cycling and jumping cannot be fully attributed to differences in muscle size (Martin, Farrar, Wagner, & Spirduso, 2000; Ferreti et al., 1994). We hypothesised that a differential joint-dependent development of maximum power could be a potential contributor. The fact that we found age x joint interactions only during the isometric condition and not the dynamic conditions let us speculate that this might not be the case. This finding is in agreement with Korff and Jensen (2007). These authors found little relative differences between knee and ankle power during sub-maximal cycling in children between 5 and 10 years of age. However, Korff and Jensen did find that maximum hip joint power was relatively greater in older compared to younger children. The present study does not rule out that the development of hip joint power might not be in line with the knee and ankle joints. This deserves further study. In practice, our results suggest that during tasks such as the isometric leg press or when isometrically pushing in activities such as rugby or judo, children's performance may be impaired because of the lack of torque

production differentiation between the ankle and knee joints. Strength training in children might be best focused on developing knee extensors isometric strength to cope with this.

A possible explanation of the observed age x joint interaction in maximum strength is a muscle-specific development of recruiting muscles. Therefore, the second hypothesis was posed to test that a possible age by joint interaction in peak torques would be accompanied by muscle-specific differences in the levels of activation. In contrast to this hypothesis, the age by joint interaction for magnitude of muscle activity was non-significant. These results are in agreement with Belanger and McComas (1989) who did not find a significant difference in muscle activation between 11 year-old children and 16.4 year-old adolescents. Our results suggest that the development of the ability to recruit the plantarflexor and knee extensor muscles is not muscle-specific. It means that the age differences in recruitment are independent of joint and speed. This may suggest that at both joints tested there was no difference in how the two age groups activated their muscles.

In summary, our results demonstrated that children exhibited a differential development of maximum torque production across the lower limb joints under static but not under dynamic conditions. This could be due to the fact that children took advantage of the stretch and shortening cycle to produce a greater torque at the knee during dynamic tasks. Our results also suggest that the differential development in maximum torque under isometric conditions is not due to a differential development to activate their muscles. A more likely cause for our observed differences is a muscle-specific development in cross sectional area and

muscle structure/architecture. Future research should be aimed at determining the sources of the muscle specific development in strength specifically.

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Appendix

Appendix A: Extended results

In order to test our result's robustness, we normalised and analysed EMG data in different ways. Results from the different analyses are presented below. An age by joint MANOVA with repeated measures was performed. When the age by joint interaction was significant, follow up ANOVAs were performed for each dependent variable. Effect sizes were calculated by dividing the difference in group means by the pooled standard deviation. Cohen's (1988) classification scheme was used to interpret the effect sizes. Effect sizes smaller than 0.5 are interpreted as a small effect. Effect sizes greater than 0.5 and smaller than 0.8 are interpreted as a moderate effect. Effect sizes greater than 0.8 are interpreted as a large effect (Cohen, 1988).

Similar analysis was performed to test the joint dependence of the age-related changes in the magnitude of muscle activity. An age by muscle (i.e., GM and VL) MANOVA with repeated measures has been performed.

A - IMVC normalised to the highest value among the four velocities

Wilk's Lambda = 0.655, F (14, 1) = 1.45, $p > .05$

B - IMVC normalised to 3 averaged velocities

Wilk's Lambda = 0.912, F (14, 1) = 1.35, $p > .05$

C - IMVC normalised to each velocity

Wilk's Lambda = 0.808, F (14, 1) = 0.949, $p > .05$

D - Each velocity normalised to IMVC

Wilk's Lambda = 0.674, F (14, 1) = 1.932, $p > .05$

E - RMS values normalised to peak torque (EMG-Torque ratio)

Wilk's Lambda = 0.452, F (14, 1) = 3.328, $p > .05$

F - Torque values normalised to body mass

Wilk's Lambda = 0.639, F (18, 1) = 2.115, $p > .05$

Table A. Effect sizes describing pairwise joint differences in magnitude of muscle activity when IMVCs were normalised to the highest value among the four velocities (*GM* Gastrocnemius Medialis, *VL* Vastus Lateralis, *CH* children, *AD* adults).

Comparison	Speeds ($deg.s^{-1}$)			
	MVC	30	75	120
GM-VL (CH)	0.17	0.09	0.69	0.29
GM-VL (AD)	0.18	1.13	0.83	0.31

Table B. Effect sizes describing pairwise joint differences in magnitude of muscle activity when IMVCs were normalised to three averaged velocities (*GM* Gastrocnemius Medialis, *VL* Vastus Lateralis, *CH* children, *AD* adults).

Comparison	
GM-VL (CH)	0.35
GM-VL (AD)	0.48

Table C. Effect sizes describing pairwise joint differences in magnitude of muscle activity when IMVCs were normalised to each velocity (*GM* Gastrocnemius Medialis, *VL* Vastus Lateralis, *CH* children, *AD* adults).

Comparison	Speeds ($deg.s^{-1}$)		
	30	75	120
GM-VL (CH)	0.26	0.58	0.01
GM-VL (AD)	0.69	0.46	0.28

Table D. Effect sizes describing pairwise joint differences in magnitude of muscle activity when each velocity value was normalised to IMVCs (*GM* Gastrocnemius Medialis, *VL* Vastus Lateralis, *CH* children, *AD* adults).

Comparison	Speeds ($deg.s^{-1}$)		
	30	75	120
GM-VL (CH)	0.04	0.34	0.10
GM-VL (AD)	0.53	0.40	0.21

Appendix B: Raw data

Table A1. Ankle torque values for each adult participant (n = 10)

Ankle	**MVC**	**30**	**75**	**120**
Ad1	104.67	78.77	57.45	46.07
Ad2	146.96	100.63	80.98	70.69
Ad3	227.60	146.17	117.50	84.42
Ad4	127.38	115.23	86.45	57.82
Ad5	149.30	130.29	118.12	94.96
Ad6	232.74	158.53	124.62	95.85
Ad7	169.92	115.20	83.24	69.70
Ad8	259.85	186.13	125.22	108.23
Ad9	173.5	133.64	103.83	28.13
Ad10	182.49	152.73	107.71	79.66
Mean	177.44	131.73	100.51	73.55
SD	49.43	31.00	22.57	24.50

Table A2. Knee torque values for each adult participant (n = 10)

Knee	**MVC**	**30**	**75**	**120**
Ad1	216.62	179.97	170.87	154.17
Ad2	244.56	190.88	171.53	138.48
Ad3	363.57	278.78	251.63	208.19
Ad4	211.24	160.23	153.63	149.56
Ad5	198.85	176.33	161.16	138.59
Ad6	394.60	308.59	239.49	198.74
Ad7	240.82	154.89	152.11	144.40
Ad8	395.24	298.85	280.91	250.61
Ad 9	279.27	191.06	198.38	198.87
Ad10	249.41	169.71	120.93	119.80
Mean	279.42	210.93	190.06	170.14
SD	76.34	59.85	51.26	41.42

Table A3. Ankle and knee torque values normalised to body mass for each child participant (n = 10). Coefficients of variance (CV) are presented for both normalisation techniques (i.e., torque normalised to body weight and absolute values).

	Ankle				Knee			
	MVC	30	75	120	MVC	30	75	120
Ch1	2.51	0.76	0.45	0.43	2.72	1.72	1.66	1.65
Ch2	1.46	0.86	0.59	0.4	2.92	2.07	1.62	1.36
Ch3	2.6	1.17	0.89	0.75	2.88	2.68	2.25	2.07
Ch4	1.61	0.85	0.55	0.63	2.22	1.7	1.31	1.4
Ch5	2.07	1.44	1.00	0.9	2.58	2.41	2.1	1.83
Ch6	4.09	0.82	0.45	0.45	2.17	1.67	1.41	0.91
Ch7	1.37	1.35	0.87	0.59	2.3	1.76	1.7	1.42
Ch8	3.55	0.62	0.32	0.4	2.3	1.88	1.88	1.56
Ch9	1.8	1.24	1.36	0.97	2.26	2.07	2.13	1.86
Ch10	1.95	1.27	0.74	0.63	2.88	2.03	1.79	1.85
Mean	2.30	1.04	0.72	0.62	2.52	2.00	1.79	1.59
SD	0.91	0.29	0.31	0.21	0.31	0.33	0.31	0.34
CV (%)	39.33	27.58	43.59	33.43	12.11	16.60	17.32	21.09
CV non-norm to BM	25.27	39.36	48.15	45.00	27.24	35.96	35.71	37.23

Table A4. Ankle and knee torque values normalised to body mass for each adult participant (n = 10). Coefficients of variance (CV) are presented for both normalisation techniques (i.e., torque normalised to body weight and absolute values).

	Ankle				Knee			
	MVC	30	75	120	MVC	30	75	120
Ad1	1.62	1.22	0.89	0.71	3.34	2.78	2.64	2.38
Ad2	2.06	1.41	1.14	0.99	3.43	2.68	2.41	1.94
Ad3	2.54	1.63	1.31	0.94	4.06	3.11	2.81	2.32
Ad4	1.74	1.57	1.18	0.79	2.89	2.19	2.1	2.04
Ad5	2.11	1.85	1.67	1.35	2.82	2.5	2.28	1.96
Ad6	2.68	1.83	1.44	1.11	4.55	3.56	2.76	2.29
Ad7	2.16	1.46	1.06	0.88	3.06	1.97	1.93	1.83
Ad8	2.36	1.69	1.14	0.98	3.58	2.71	2.55	2.27
Ad9	2.39	1.84	1.43	0.39	3.85	2.64	2.74	2.74
Ad10	2.64	2.21	1.56	1.15	3.61	2.46	1.75	1.74
Mean	2.23	1.67	1.28	0.93	3.52	2.66	2.40	2.15
SD	0.36	0.28	0.24	0.26	0.54	0.45	0.37	0.30
CV (%)	16.17	16.75	18.91	28.38	15.31	16.78	15.49	14.09
CV non-norm to BM	27.86	23.53	22.46	33.31	27.32	28.37	26.97	24.34

Table A5. Gastrocnemius Medialis (GM) EMG values for each adult participant (n = 8)

GM	**MVC**	**30**	**75**	**120**
Ad1	0.2516	0.2056	0.1866	0.1853
Ad2	0.2126	0.2390	0.2791	0.2817
Ad3	0.3903	0.4001	0.3869	0.4256
Ad4	0.1261	0.2430	0.2102	0.2390
Ad5	0.1084	0.1777	0.2201	0.2116
Ad6	0.2665	0.2624	0.2991	0.2883
Ad7	0.1515	0.1568	0.1658	0.1724
Ad8	0.2144	0.2151	0.2150	0.2213
Mean	0.2152	0.2375	0.2454	0.2532
SD	0.0910	0.0744	0.0723	0.0809

Table A6. Vastus Lateralis (VL) EMG values for each adult participant (n = 8)

VL	**MVC**	**30**	**75**	**120**
Ad1	0.2868	0.3246	0.3393	0.4116
Ad2	0.1669	0.1599	0.1988	0.2110
Ad3	0.1907	0.2000	0.2132	0.2304
Ad4	0.3643	0.2707	0.3035	0.3653
Ad5	0.1151	0.1575	0.1982	0.1969
Ad6	1.2755	1.4271	1.0913	1.0246
Ad7	0.3209	0.1851	0.2487	0.3070
Ad8	0.4949	0.4118	0.4381	0.4098
Mean	0.4019	0.3921	0.3789	0.3946
SD	0.3733	0.4276	0.2995	0.2688

Table A7. Ankle torque values for each child participant (n = 10)

Ankle	**MVC**	**30**	**75**	**120**
ch1	91.00	27.55	16.27	15.43
ch2	43.84	25.92	17.72	12.05
ch3	116.51	61.52	46.78	39.04
ch4	94.71	38.03	24.70	28.40
ch5	94.11	84.55	59.03	52.91
ch6	124.03	37.53	20.32	20.59
ch7	81.77	40.95	26.46	17.77
ch8	126.19	37.02	19.17	23.94
ch9	85.31	44.17	48.21	34.44
ch10	92.48	60.22	35.11	29.97
Mean	95.00	45.74	31.38	27.45
SD	24.01	18.00	15.11	12.35

Table A8. Knee torque values for each child participant (n = 10)

Knee	**MVC**	**30**	**75**	**120**
ch1	98.67	62.42	60.36	59.78
ch2	87.85	62.26	48.83	41.05
ch3	151.11	140.62	117.90	108.38
ch4	99.66	76.14	58.64	62.69
ch5	151.80	141.89	123.98	107.92
ch6	98.54	76.18	64.29	41.45
ch7	69.69	53.33	51.57	43.06
ch8	137.60	112.48	112.02	93.29
ch9	80.32	73.54	75.54	65.86
ch10	136.66	96.55	84.99	87.87
Mean	111.19	89.54	79.81	71.14
SD	30.29	32.20	28.50	26.49

Table A9. Gastrocnemius Medialis (GM) EMG values for each child participant (n = 8)

GM	**MVC**	**30**	**75**	**120**
Ch1	0.2003	0.1427	0.1504	0.1878
Ch2	0.1240	0.1604	0.1374	0.1708
Ch3	0.1998	0.2478	0.3094	0.3375
Ch4	0.1299	0.0925	0.0992	0.1360
Ch5	0.1283	0.2139	0.2021	0.2197
Ch6	0.1833	0.1379	0.1117	0.1623
Ch7	0.3336	0.3043	0.2756	0.2998
Ch8	0.1370	0.0702	0.0349	0.0948
Mean	0.1795	0.1712	0.1651	0.2011
SD	0.0703	0.0791	0.0922	0.0818

Table A10. Vastus Lateralis (VL) EMG values for each child participant (n = 8)

VL	**MVC**	**30**	**75**	**120**
Ch1	0.2988	0.2543	0.3096	0.4274
Ch2	0.1916	0.1941	0.2078	0.2133
Ch3	0.4042	0.3588	0.3473	0.4129
Ch4	0.1569	0.1592	0.1342	0.1585
Ch5	0.1220	0.1879	0.2001	0.2074
Ch6	0.4932	0.3407	0.3341	0.3155
Ch7	0.4646	0.3484	0.5083	0.4662
Ch8	0.1083	0.1177	0.1484	0.1299
Mean	0.2800	0.2451	0.2737	0.2914
SD	0.1571	0.0943	0.1255	0.1316

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Appendix C: RESEARCH PARTICIPATION FORM (For adult participants)

Age-related differences in muscle strength and power

You are invited to participate in a study investigating the age-related differences in muscle strength across different joints. My name is Romain Denis and I am a MPhil student in Biomechanics at Brunel University. I am the principal investigator of this research study.

If you decide to participate, you will perform a warm-up/familiarisation session which will last about 15 min. You will be seated in a safe, specially designed, strength testing machine that records your force production during simple leg movements. We will adjust the machine to your individual body size. We will be careful to avoid any discomfort. If you want to stop the strength testing machine at any time during testing, you will be able to press an emergency stop button. During the testing, we will ask you to flex and extend your ankle and knee joints at constant speeds. You will have sufficient resting time between the trials.

The total testing time will take no longer than 90 minutes, including the time it takes to familiarise you with the laboratory.

Your personal information will remain confidential, and we will not disclose it without your permission. There will be no direct benefit to you following your participation in this study. Your assistance through participation will help us to better understand the age-related differences in muscle strength across different joints.

Your decision whether or not to participate will not affect your association with Brunel University. If you decide not to participate, you will be free to withdraw from this study at any time without penalty.

In the unlikely event of injury as a result of your participation in this study, no treatment will be provided, and no payment can be provided in the event of a medical problem. Basic first aid will be provided at the time of injury and you will be encouraged to consult your General Practitioner.

If you have any questions after reading this form, please contact Romain Denis (Ph: 07962 631014; e-mail: romain.denis@brunel.ac.uk) or Dr Thomas Korff (thomas.korff@brunel.ac.uk). If you have additional questions later (including questions regarding the outcome of this study), we will be happy to answer them.

School of Sport and Education
Health Questionnaire (Adult Participant)

Brunel UNIVERSITY WEST LONDON

Name: …….
Address: …….
…….
…….
…….
Phone: …….

Name of the responsible investigator for the study: ……..

Please answer the following questions. If you have any doubts or difficult with the questions, please ask the investigator for guidance. These questions are to determine whether the proposed exercise is appropriate for you. Your answers will be kept strictly confidential.

1	Are you male or female?		
2	What is your date of birth? Day……Month……Year…….. Your age is …… years		
3	When did you last see your doctor? In the: Last week ……. Last month…….Last six months…… Year……. More than a year……		
4	Are you currently taking any medication?	Yes	No
5	Has a doctor ever advised you not to take vigorous exercise?	Yes	No
6	Has your doctor ever said you have 'heart trouble'?	Yes	No
7	Has your doctor ever said you have high blood pressure?	Yes	No
8	Have you ever taken medication for blood pressure or your heart?	Yes	No
9	Do you feel pain in your chest when you undertake physical activity?	Yes	No
10	In the last month, have you had pains in your chest when not doing any physical activity?	Yes	No
11	Has your doctor (or anyone else) said that you have raised blood cholesterol?	Yes	No
12	Have you had a cold or feverish illness in the last month?	Yes	No
13	Do you ever lose balance because of dizziness, or do you ever lose consciousness?	Yes	No
14	Do you suffer from back pain? If so, does it ever prevent you from exercising?	Yes	No No
15	Do you suffer from asthma?	Yes	No
16	Do you have any joint or bone problems that may be made worse by exercise?	Yes	No

17	Has your doctor ever said you have diabetes?	Yes	No
18	Have you ever had viral hepatitis?	Yes	No
19	If you are female, to your knowledge, are you pregnant?	Yes	No
20	Do you know of any reason, not mentioned above, why you should not exercise?	Yes	No
21	Are you accustomed to vigorous exercise (an hour or so a week)?	Yes	No

I have completed the questionnaire to the best of my knowledge and any questions I had, have been answered to my full satisfaction.

Signature:

MODEL CONSENT FORM (For Adult Participants)

Name in capitals:

The participant should complete the whole of this sheet him/herself		
	Please tick the appropriate box	
	YES	**NO**
Have you read the Research Participant Information Sheet?	☐	☐
Have you had an opportunity to ask questions and discuss this study?	☐	☐
Have you received satisfactory answers to all your questions?	☐	☐
Who have you spoken to?		
Do you understand that you will not be referred to by name in any report concerning the study?	☐	☐
Do you understand that you are free to withdraw from the study:		
- **at any time**	☐	☐
- **without having to give a reason for withdrawing?**	☐	☐
- ***(where relevant)*** **without affecting your future care?**	☐	☐
Do you agree to take part in this study?	☐	☐

Signature of Research Participant:
Date:
Name of Research Participant in capitals:
<u>Witness statement</u>
I am satisfied that the above-named has given informed consent.
Witnessed by:

Date:
Name in capitals:

RESEARCH PARTICIPATION FORM (For parents/guardian)

Age-related differences in muscle strength and power

Your child is invited to participate in a study investigating the age-related differences in muscle strength and power across the different joints. My name is Romain Denis and I am a MPhil student in Biomechanics at Brunel University. I am the principal investigator of this research study.

If you agree for your child to participate, he will perform a warm-up/familiarisation session which will last about 15 min. Your child will be seated in a safe, and specially designed, strength testing machine that records his force production during simple leg movements. We will adjust the machine to your child's individual body size. We will be careful to avoid any discomfort. If s/he wants to stop the strength testing machine at any time during testing, he will be able to press an emergency stop button. During the testing, we will ask your child to flex and extend her/his ankle and knee joints at constant speeds. He will have sufficient resting time between the trials.

The total testing time will take no longer than two hours, including the time it takes to familiarise your child with the laboratory.

Your child's personal information will remain confidential, and we will not disclose it without your permission. There will be no direct benefit to you and your child following your participation in this study. Your child's assistance through participation will help us to better understand the age-related differences in muscle strength across different joints.

Your child's decision whether or not to participate will not affect his association with Brunel University. If your child decides not to participate, he will be free to withdraw from this study at any time without penalty.

In the unlikely event of injury as a result of your child participation in this study, no treatment will be provided, and no payment can be provided in the event of a medical problem. Basic first aid will be provided at the time of injury and your child will be encouraged to consult your General Practitioner.

If you have any questions after reading this form, please contact Romain Denis (Ph: 07962 631014; e-mail: romain.denis@brunel.ac.uk) or his supervisor Dr Thomas Korff (thomas.korff@brunel.ac.uk). If you have additional questions later (including questions regarding the outcome of this study), we will be happy to answer them.

RESEARCH PARTICIPATION FORM (For children)

Age-related differences in muscle strength and power

You are invited to participate in an experiment about children's muscle strength. My name is Romain Denis and I am a student at Brunel University.

If you decide to participate, you will be seated in a safe, and specially designed, strength testing machine and I will ask you to push your leg as hard and as fast as possible against the machine. This will be done at different speeds, for your ankle and knee.

We will adjust the machine to your individual body size. We will be careful to avoid any discomfort. If you want to stop the strength testing machine at any time during testing, you will be able to press an emergency stop button. During the testing, we will ask you to flex and extend your ankle and knee joints at constant speeds. You will have sufficient resting time between the trials.

This test will be done to measure your muscle strength and power characteristics.

If you feel pain or discomfort during testing, please let me know. You can stop the testing at any time.

School of Sport and Education
Health Questionnaire (Child participant)

Brunel UNIVERSITY WEST LONDON

Name: …….
Address: …….
…….
…….
…….
Phone: …….

Name of the responsible investigator for the study: ……..

Please answer the following questions. If you have any doubts or difficult with the questions, please ask the investigator for guidance. These questions are to determine whether the proposed exercise is appropriate for you. Your answers will be kept strictly confidential.

1	Are you male or female?		
2	What is your date of birth? Day……Month……Year…….. Your age is …… years		
3	When did you last see your doctor? In the: Last week ……. Last month…….Last six months…… Year……. More than a year……		
4	Are you currently taking any medication?	Yes	No
5	Has a doctor ever advised you not to take vigorous exercise?	Yes	No
6	Has your doctor ever said you have 'heart trouble'?	Yes	No
7	Has your doctor ever said you have high blood pressure?	Yes	No
8	Have you ever taken medication for blood pressure or your heart?	Yes	No
9	Do you feel pain in your chest when you undertake physical activity?	Yes	No
10	In the last month, have you had pains in your chest when not doing any physical activity?	Yes	No
11	Has your doctor (or anyone else) said that you have raised blood cholesterol?	Yes	No
12	Have you had a cold or feverish illness in the last month?	Yes	No
13	Do you ever lose balance because of dizziness, or do you ever lose consciousness?	Yes	No
14	Do you suffer from back pain? If so, does it ever prevent you from exercising?	Yes	No No
15	Do you suffer from asthma?	Yes	No
16	Do you have any joint or bone problems that may be made worse by exercise?	Yes	No

17	Has your doctor ever said you have diabetes?	Yes	No
18	Have you ever had viral hepatitis?	Yes	No
19	If you are female, to your knowledge, are you pregnant?	Yes	No
20	Do you know of any reason, not mentioned above, why you should not exercise?	Yes	No
21	Are you accustomed to vigorous exercise (an hour or so a week)?	Yes	No

I have completed the questionnaire to the best of my knowledge and any questions I had, have been answered to my full satisfaction.

Child signature:

Parent/Guardian signature:

MODEL CONSENT FORM (For Children and Parents/Guardian)

The participant should complete the whole of this sheet him/herself

	Please tick the appropriate box YES	NO
Have you read the Research Participant Information Sheet?	☐	☐
Have you had an opportunity to ask questions and discuss this study?	☐	☐
Have you received satisfactory answers to all your questions?	☐	☐
Who have you spoken to?		
Do you understand that you will not be referred to by name in any report concerning the study?	☐	☐
Do you understand that you are free to withdraw from the study:		
- **at any time**	☐	☐
- **without having to give a reason for withdrawing?**	☐	☐
- ***(where relevant)*** **without affecting your future care?**	☐	☐
Do you agree to take part in this study?	☐	☐

Signature of Research Participant:

Signature of the Parent's Research Participant:

Date:

Name of Research Participant in capitals:

Name of the Parent's Research Participant:

<u>Witness statement</u>

I am satisfied that the above-named has given informed consent.

Witnessed by:

Date