Neuromuscular adaptations in endurance-trained boys and men

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ABSTRACT

Competitive sports participation in youth is becoming increasingly more common in the Western world. It is widely accepted that sports participation, specifically endurance training, is beneficial for physical, psychomotor, and social development of children. The research on the effect of endurance training in children has focused mainly on health-related benefits and physiological adaptations, particularly on maximal oxygen uptake. However, corresponding research on neuromuscular adaptations to endurance training and the latter's possible effects on muscle strength in youth is lacking.

In children and adults, resistance training can enhance strength and increase muscle activation. However, data on the effect of endurance training on strength and neuromuscular adaptations are limited. While some evidence exists demonstrating increased muscle activation and possibly increased strength in endurance athletes compared with untrained adults, the neuromuscular adaptations to endurance training in children have not been examined. Thus, the purpose of this study was to examine maximal isometric torque and rate of torque development (RTD), along with the pattern of muscle activation during elbow and knee flexion and extension in muscle-endurance-trained and untrained men and boys.

Subjects included 65 males: untrained boys (n=18), endurance-trained boys (n=12), untrained men (n=20) and endurance-trained men (n=15). Maximal isometric torque and rate of torque development were measured using an isokinetic dynamometer (Biodex III), and neuromuscular activation was assessed using surface electromyography (SEMG). Muscle strength and activation were assessed in the dominant arm and leg, in a cross-balanced fashion during elbow and knee flexion and extension. The main variables

included peak torque (T), RTD, rate of muscle activation (Q_{30}), Electro-mechanical delay (EMD), time to peak RTD and co-activation index.

Age differences in T, RTD, electro-mechanical delay (EMD) and rate of muscle activation (Q_{30}) were consistently observed in the four contractions tested. Additionally, Q_{30}, normalized for peak EMG amplitude, was consistently higher in the endurance-trained men compared with untrained men. Co-activation index was generally low in all contractions. For example, during maximal voluntary isometric knee extension, men were stronger, had higher RTD and Q_{30}, whether absolute or normalized values were used. Moreover, boys exhibited longer EMD (64.8 $\pm$ 18.5 ms vs. 56.6 $\pm$ 15.3 ms, for boys and men respectively) and time to peak RTD (112.4 $\pm$ 33.4 ms vs. 100.8 $\pm$ 39.1 ms for boys and men, respectively). In addition, endurance-trained men had lower T compared with untrained men, yet they also exhibited significantly higher normalized Q_{30} (1.9 $\pm$ 1.2 vs. 1.1 $\pm$ 0.7 for endurance-trained men and untrained men, respectively). No training effect was apparent in the boys.

In conclusion, the findings demonstrate muscle strength and activation to be lower in children compared with adults, regardless of training status. The higher Q_{30} of the endurance-trained men suggests neural adaptations, similar to those expected in response to resistance training. The lower peak torque may suggest a higher relative involvement of type I muscle fibres in the endurance-trained athletes.

Future research is required to better understand the effect of growth and development on muscle strength and activation patterns during dynamic and sub-maximal isometric contractions. Furthermore, training intervention studies could reveal the effects

of endurance training during different developmental stages, as well as in different muscle groups.

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LIST OF ABBREVIATIONS

CV: Coefficient of variation

EMD: Electromechanical delay

EMG: Electromyography

mCSA: Muscle cross-sectional area

MHC: Myosin heavy chain

MPF: Mean power frequency

MU: Motor unit

MVC: Maximal voluntary contraction

PHV: Peak height velocity

RTD: Rate of torque development

RMS: Root mean square

SEMG: Surface electromyography

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CHAPTER 1: INTRODUCTION

1.1 Background

Competitive sports participation in youth is becoming increasingly more common in the Western world. More children are participating in intense training at an ever younger and younger age. This is particularly true for swimmers, for whom training can begin as young as 7 years old. At 9-10 years of age, swimmers may be training intensely 6 hr per week or more.

It is widely accepted that sports participation, specifically endurance training, is beneficial for physical, psychomotor, and social development of children. The research on the effect of endurance training in children has focused mainly on health-related benefits (Janz et al. 2002) and physiological adaptations, particularly on maximal oxygen uptake (Armstrong et al. 2007). However, corresponding research on neuromuscular adaptations to endurance training and the latter's possible effects on muscle strength in youth is lacking.

The neuromuscular system develops from birth through adulthood. Independent of changes associated with growth and maturation, adaptive changes in maximal muscle strength, muscle activation, as well as in the maximal rate of force development can also result from training (Aagaard, 2003).

It is assumed that untrained adults cannot fully activate their motor units or cannot activate them at an optimal firing rate during maximal voluntary contraction (De Luca, 1982). The ability of untrained pre-pubertal boys to activate their neuromuscular system has been suggested to be lower than adults' (Passuke et al. 2000; Belanger & McComas, 1989). Furthermore, some researchers have suggested that children are less able to recruit

or utilize their higher-threshold motor units compared with adults (Asai & Aoki 1996; Falk and Dotan, 2006). Consequently, it has been proposed that the neuromuscular system of children may be more adaptive to a training stimulus (Halin et al. 2002). Thus, training induces specific alterations in neuromuscular control, depending on the nature and intensity of training (Bencke, 2002), and possibly, on the developmental stage during which training takes place (Rowland, 2005).

In children and adults, resistance training can enhance strength and increase muscle activation (Ramsay et al. 1990; Sale, 1988). However, data on the effect of endurance training on strength and neuromuscular adaptations are limited. While some evidence exists demonstrating increased muscle activation and possibly increased strength in endurance athletes compared with untrained adults (Lattier et al. 2003; Lucia et al. 2000), there are no comparable data in children. That is, the neuromuscular adaptations to endurance training in children have not been examined.

The present study compared endurance-trained boys and men to untrained age-matched controls. The research sought to investigate whether swim training, where muscle endurance is emphasized, affects muscle strength and activation and if so, whether the training effect is different between children and adults.

1.2 Purpose

The purpose of the study was to examine maximal isometric torque and rate of torque development, along with the pattern of muscle activation during elbow and knee flexion and extension in muscle-endurance-trained and minimally-active boys and in muscle-endurance-trained and minimally-active men.

1.3 Study Hypotheses

It was hypothesized that:

1. Peak torque and rate of torque development will be lower in children compared with adults. The differences will be seen when strength is corrected for body size or peak torque, respectively.
2. Peak torque and rate of torque development will be higher in athletes compared with non-athletes. The differences will be seen when strength is corrected for body size or for peak torque, respectively.
3. The rate of muscle activation will be lower in children compared with adults.
4. The rate of muscle activation will be higher in athletes compared with non-athletes.
5. There will be no difference in the training effect on muscle activation and strength in children compared with adults.

CHAPTER 2: REVIEW OF LITERATURE

2.1 Changes in Muscle strength and performance development with growth

Muscle strength is a complex, performance-related fitness component, which is underpinned by muscular, neural and mechanical factors. Strength is defined as the maximal force, torque or moment development by a muscle or muscle group during one maximal voluntary or evoked action of unlimited duration, at a specified velocity of movement (Knuttgen & Kraemer, 1987). The maximum force exerted by a muscle is related to the cross-sectional area of the muscle, taking into account the angle of pennation, and on the pattern of excitation (MacIntosh et al. 2006).

Strength may be expressed in absolute values, or relative to body mass or other body size measures such as, muscle cross sectional area (Sale & Spriet, 1996). When comparing children with adults, strength is commonly expressed relative to body mass or cross sectional area.

2.1.1 Muscle strength

The development of muscular strength during growth is related to factors such as age, body size, and sexual maturation. The strength increase during growth and maturation is affected by various factors such as neural, hormonal and biomechanical factors which cause the appropriate structural and functional adaptations for strength gain (Blimkie, 1989). These factors will be further discussed below (see section 2.2).

The acceleration in growth during puberty is characterized by an increase in height as well as in body mass. This acceleration in growth is accompanied by changes in muscle strength and performance.

During growth and maturation, boys increase their isometric strength in a linear fashion from early childhood up until the onset of puberty, around the age 13 to 14 yrs when there is acceleration in strength development (De Ste Croix, 2007). These strength gains were suggested to be associated with increases in muscle mass, which occur with growth (Froberg & Lammert, 1996). In a 2-yrs longitudinal study Maffulli et al. (1994), reported that the rate of increase of strength per body mass in boys was still increasing from the time of boy's peak height velocity (PHV) to around age 18. Although, on average boys tend to gain strength in proportion to body size, they reach peak strength gain about 1.2 years after peak gain in height (Peak height velocity) and 0.8 years after peak weight velocity (Malina et al. 2004; Blimkie, 1989).

Although size differences between children and adults might account for much of the differences in strength between the two groups, adults show higher values of strength than children do even when normalized to size measurement (Lambertz et al. 2003; Grosset et al. 2005; Halin et al. 2003; Seger & Thorstensson, 2000; Wood et al. 2004). Consequently, additional factors, such as muscle activation or composition, must account for the observed strength differences.

2.1.2 Rate of torque development (RTD)

The rate of torque development (RTD) is generally defined as the rate of rise in contractile force at the onset of contraction and determined as the slope in the force time curve (Hakkinen & Komi, 1986; Aagaard et al. 2002). It is an important variable in assessing the explosive strength qualities of the neuromuscular system (Aagaard et al. 2002).

The RTD in static and dynamic contractions is suggested to relate to several factors, including muscle fibres composition and pattern of recruitment (Mero et al. 1991), as well as the series elastic components of the tendon-muscle complex that influence the transmission of the force exerted by muscle fibres to the bone (Lambertz et al. 2003; Fukunaga et al. 1997). This was supported by several studies, which suggested that the tendon structures would affect the force-time curve, and consequently the RTD (Going et al. 1987; Cavagna & Komi, 1979). Other factors capable of affecting RTD may include excitation-contraction coupling, and muscle fibre conduction velocity. These have been examined in children only to a limited extent and with inconsistent results (Grosset et al. 2005; Garcia et al. 2000).

Few studies have reported differences in RTD between children and adults. Three studies have examined the RTD in boys during isometric elbow flexion and one study examined RTD in the triceps surae, all suggesting that RTD is lower in children compared with adults (Falk et al. 2009b; Going et al. 1987; Asai & Aoki, 1996; Grosset et al. 2005). Asai & Aoki (1996) examined force development during dynamic and static contractions in 6-year-old boys and adults. During isometric elbow flexion contraction, children exhibited lower RTD values than adults. With an increase in pre-tension, the adults' RTD showed a tendency to decrease, whereas in children, there was no change in RTD. The authors suggested that during the low pre-tension levels, slow twitch fibres acted dominantly. As pre-tension increased, the fast twitch fibres were progressively recruited. Therefore, at a higher pre-tension, it was progressively more difficult for subjects to generate more force by the recruitment of the fast twitch fibres or the increase in their firing rate. This was the explanation for the observed decrease of RTD with an

increase in pre-tension in the adults. However, this pattern was not found in the children, which suggests that the mechanisms of the recruitment and the changes in firing rate of motor units based on size principal might not be well established in childhood.

Going et al. (1987) compared the pattern of force production during maximal voluntary static contraction in children, aged 8-11 years with adult literature. While they did not report RTD per se, they reported that a greater proportion of maximum force is reached more rapidly by adults than by children, indicating that children have lower rates of torque development than do adults. Adults at the beginning of the plateau phase generated about 90% of their maximal force, while children generated only 75% to 80% at that stage. Furthermore, after reaching the force plateau it took children two to four times longer than adults to reach their force peak.

Only one study looked at the effect of age on RTD in the lower extremities. Grosset et al. (2005) analyzed contractile properties of the plantar flexors in prepubertal children (7-11 yrs) during an evoked twitch and during MVC. Although the authors did not find any significant differences in twitch characteristics (contraction time and half relaxation time) between children and adults, indicating similar muscle composition in the two age groups, they did find a significant increase in RTD with age during maximal voluntary contraction. The latter indicates that factors other than muscle fibre composition play a role in the age-related differences in RTD.

2.2 Factors Affecting Muscle Performance during Growth

Several factors have been linked with the age-associated differences in muscle strength and RTD. The interaction between those factors is complex, and sometimes hard to indentify.

2.2.1 Body size

The size, shape and proportions of the body influence strength development. According to De Ste Croix (2007), stature and mass appear to be important explanatory variables in the development of muscle strength. Moreover, among adults the maximal force that can be generated is primarily a function of muscle size (Sale & Spriet, 1996).

2.2.1.1 Mass and stature

In healthy children, muscle growth might be expected to respond to a number of factors including the stretch imposed by growing long bones and the mechanical stress of increasing body weight (Parker et al. 1990).

Most studies try to relate strength to body mass. Sale & Spriet (1996), illustrate that both body mass and absolute strength increase with growth. Body mass was highly correlated with maximal voluntary isometric strength of both elbow flexors and knee extensors in males 9 to 18 year old (Blimkie, 1989). More so, Parker and others (1990) found that in the quadriceps, weight-bearing muscles, the increasing strength was associated with the increase in height, together with an increasing body mass during growth. This was supported by Round et al. (1999) who reported that isometric knee extensor strength increased in proportion to the increase in stature and mass in 8 – 13 years old girls.

Some authors suggested that changes in stature might promote changes in strength during maturation. There is a high correlation between fibre area and body height during the growing years (Sale & Spriet, 1996). Wood et al. (2004) hypothesized that growth of the long bones (e.g., humerus) may stimulate muscle development and strength. Stretch is known to be a factor leading to muscle growth (Frankeny et al. 1983) and during development, a major component of gain in height is the increasing length of the long bones. The resulting stretch of the limb muscles would appear to provide a stimulus for muscle development leading to strength gains in children (Parker et al. 1990).

Both stature and mass appear to be important explanatory variables of the age-associated development in strength and therefore the age-related differences between children and adults. Muscle strength is expected to relate to the cross-sectional area of the contracting muscle, which by dimensionality theory should relate to height^2. However, in order for this to be true, subjects of different size have to be geometrically similar. Nevertheless, children and adults are not geometrically similar. Specifically, children have relatively larger heads and shorter extremities than adults (Rowland, 2005). Furthermore, muscle architecture varies between different muscle groups, and may not match the simple geometric assumptions of the dimensionality theory. Therefore, it has been suggested that improvements in muscular strength with maturation are related to additional factors, other than changes in segment length and muscle mass (Malina et al. 2004).

This is supported by the findings that even when correcting for body mass or stature, adults remain stronger than pre-pubertal children, indicating that other size-

independent factors contribute to the age-related differences in strength (Blimkie, 1989; De Ste Croix, 2007; Round et al. 1999).

2.2.1.2 Muscle cross-sectional area (mCSA)

There is an inconsistency in the literature, regarding the increase in strength per mCSA with age. Sale & Spriet (1996) suggested that the increase in strength from childhood to adulthood is largely due to an increase in mCSA during this period. A number of studies found evidence for the relationship between mCSA and strength in children. For example, Davies et al. (1983) measured the electrically evoked mechanical and contractile properties of the triceps surae in young children (boys and girls) and adults. During supramaximal tetanic tensions and maximal voluntary contraction (MVC), men demonstrated greater absolute strength than children (11 yr old) and adolescents (14 yr old). The adolescents were stronger than their younger counterparts in both the voluntarily and electrically evoked contractions. When muscle strength was normalized for muscle and bone cross sectional area, the differences between the groups disappeared. The authors concluded that absolute differences in voluntary and electrically evoked muscle strength in children vs. adults are a function of mCSA. Furthermore, Parker et al. (1990) suggested that elbow flexor strength in 5-17 year old boys and girls increased in a similar rate as the estimated changes in mCSA.

On the other hand, Kanehisa and colleagues (1994) reported that dynamic strength in the knee extensor muscles is proportional to muscle CSA, but remains lower in children than in young adults, regardless of gender. The same group (Kanehisa et al. 1995) investigated the development in mCSA and strength capability of reciprocal muscle groups in the upper arm and thigh in boys aged 7-18 years. The authors found that

the ratio of strength to mCSA for every muscle group tested was significantly higher in the older age-groups, compared with the younger ones. Similar findings were reported by others (Seger & Thorstensson, 2000; Grosset et al. 2008, Paasuke et al. 2000; Seger & Thorstensson, 1994). This suggests that factors other than mCSA also contribute to the development of strength. Furthermore, differences in growth rate of both mCSA and strength were found between reciprocal muscle groups, i.e., elbow flexors and extensors, as well as knee extensors and flexors (Kanehisa et al. 1995), supporting the suggestion that size-independent factors affect strength development.

The inconsistency between strength performance and that predicted on the basis of body size had been attributed both to quantitative differences such, greater relative increase in muscle mass and cross sectional area of muscle compared to height; and to qualitative changes such as: neural or biochemical changes within motor units occurring during development and maturity (Blimkie, 1989). Indeed, De Ste Croix (2007), in his review pointed out that while simple body dimensions appear to play an important role in strength development in children, only 40 – 70% of the variance in strength scores of 5 to 17 yr old children could be accounted for by age, sex, stature and body mass, leaving a large portion of the variance unexplained. Thus, factors other than size differences contribute to the difference in isometric strength across ages.

2.2.2 Hormones

An important consideration regarding the development of muscle function and strength is the changes in hormone levels such as testosterone, growth hormone and estrogen. Strength development during puberty and adolescence has been associated with elevated levels of circulating androgen hormones (Hansen et al. 1999). Testosterone

stimulates anabolic processes in skeletal muscle (Malina et al. 2004) and is believed to be the most active stimulator of those processes during growth (Blimkie, 1989). In males, the effects of testosterone specifically underlie the dramatic growth spurt in muscle and fat-free mass (Malina et al. 2004). Mero et al. (1991) found that in 11 to 13 year-old athletic boys, muscle fibre area correlated well with serum testosterone. The subjects with the higher level of serum testosterone were older, taller, heavier and stronger. Hansen et al. (1999) examined the association between development of strength and testosterone levels in soccer-trained boys (10-12 yrs old). They found that the increase in strength during a two-year period was related to the changes in the levels of serum testosterone, indicating that testosterone is important for development of muscle strength in boys.

The hormonal influences in skeletal muscle are complex. Androgens are not the only hormones capable of influencing anabolic processes and muscle growth. Growth hormone, the somatomedins, insulin, and the thyroid hormones are all known to be important regulators of normal somatic and muscle tissue growth. Moreover, muscle growth and strength performance may be ultimately determined by the balance between hormonally regulated anabolic and catabolic processes, in which numerous local growth factors may be involved (Blimkie, 1989).

2.2.3 Muscle composition

Muscle fibre composition might also play a role in skeletal muscle strength development (Blimkie, 1989). There are at least four types of muscle fibres, those known to be: I, IIa, IIb and IIx (MacIntosh et al. 2006). A major functional difference between the main fibre types is contraction speed. Type I muscle fibres are also called slow twitch fibres. They have high oxidative capacity, slow contractile speed, and high fatigue

resistance. Type II muscle fibres are also called fast twitch fibres. Those fibres can be further classified into IIa, IIb and IIx (MacIntosh et al. 2006). The IIa fibres are also called fast, oxidative-glycolytic fibres, while the IIb fibres are called fast-glycolytic. Type IIx fibres are the undifferentiated fibres, which at birth appear to be at a relatively large (10-20%) proportion of the infant's muscle (Elder & Kakulas, 1993). The percentage of type I fibres increase rapidly after birth at the expense of the undifferentiated fibres. From early childhood (1-3 yr old), the fibre type composition and distribution of the child attains near-adult proportions (Blimkie, 1989; Elder & Kakulas, 1993; Bell et al. 1980).

Muscle fibre type is best determined in muscle biopsies. These are very rarely performed on healthy children, for clear ethical reasons. Therefore, other techniques have been used which indirectly reflect muscle fibre type composition such as evoked twitch contractile characteristics.

Fibres can be further differentiated on the basis of mechanical or contractile characteristics. The contractile characteristics of individual motor units are defined in terms of speed of contraction and relaxation during an evoked twitch contraction. Contraction time is the elapsed time from the onset of force to attainment of peak force. Half-relaxation time is the time from peak force to half the peak force during recovery. These two variables differ between the different muscle fibre types (Blimkie, 1989). If differences exist in contractile characteristics between children and adults, and hence in fibre-type composition then those might help explain the differences in muscle performance.

Several studies have shown no significant differences in evoked twitch contractile characteristics between pre- and postpubertal children, which suggest that the fibre-type

composition of the muscles is similar in these groups (Grosset et al. 2005; Davies et al. 1983; Paasuke et al. 2000; Belanger & McComas, 1989). These findings underlie the uniformity of muscle composition in children and adults and suggest that the force generating capacity, speed of contraction and relaxation, and force/frequency characteristics remain unchanged through adolescence and early adulthood.

On the other hand, various studies indicate that the percent distribution of type II fibres is lower in early and mid-childhood compared with adulthood (Elder & Kakulas, 1993; Fournier et al. 1982; Lexell et al. 1992). Those studies reported higher proportions of type I and undifferentiated type IIx fibres during early and mid-childhood and even during adolescence when compared with adulthood.

Lexell et al. (1992) examined the increase in volume of the muscle tissue from childhood through adolescence to adulthood. Cross sections of autopsied whole vastus lateralis muscle were examined morphometrically. The authors suggested that there is a progressive increase in muscle cross sectional area from childhood to adult age, caused by an increase in mean fibre size. This is accompanied by an alteration in the fibre type proportion. The proportion of type II fibres increased significantly from approximately 35% at the age of 5 to 50% at the age of 20. Type I muscle fibres are the smallest muscle fibres, while type II are considered the largest. Therefore, with no apparent change in the total number of fibres with growth, the authors concluded that the cause for the size differences is caused by adaptive transformation of type I fibres to type II. Another explanation is that with growth, the mean fibre CSA of type II increases to a greater extent than the increase in mean fibre CSA of type I. On the other hand, Vogler & Bove

(1985) suggested that the higher percentage of type II fibres may be due to a transformation of undifferentiated fibres (type IIx) into type II fibres.

Differences in muscle fibres distribution may also account for child-adult maximal strength differences, as well as differences in the RTD between children and adults. Mero et al. (1991) examined muscle fibre characteristics and physical performance of trained athletic boys. The RTD of the knee extensors muscles was greater in subjects who had a greater than 50% type II fibres distribution in the vastus lateralis muscle, compared with subjects who had greater than 50% type I fibres distribution.

Although inconsistencies exist in the literature, it seems that the majority of the studies (Davies et al. 1983; Paasuke et al. 2000; Belanger & McComas, 1989; Davies, 1985), support the view of a similar fibre composition in children and adults. Thus, differences in muscle composition if any do not seem sufficient to account for the observed age-related strength differences.

2.2.4 Muscle activation

Another factor that may play a role in the differences in force production between children and adults may involve differences in muscle activation. A motor unit (MU) consists of a single motor-neuron body, which is located in the anterior horn of the spinal cord, and the many muscle fibres to which its axon runs. Each unit can innervate as few as three or as many as thousands of muscle fibres (Rowland, 2005). The basic function of a MU is to transform synaptic input received by the motor neuron into mechanical output by the muscle (Heckman & Enoka, 2004).

The maximal voluntary contraction (MVC) by a muscle is highly dependent upon the degree of MU activation (Komi, 1986). MU activation is the result of both the

number of MUs recruited and the firing rate of those units (Paasuke et al. 2000). Thus, an increase in force production can be achieved by either increasing the frequency of firing rate of a given MU or by recruiting additional MUs, or both. Activation of MUs during increase in force from very light up to a maximal contraction follows a pattern, according to which firing frequency and size of newly recruited MUs increase with increasing force (Finsterer, 2001).

The most important influence on the order in which MUs are recruited is the size of the motor neuron. This association has become known as the "Henneman size principle" (Duchateau, et al. 2006). The "size principle" states that MUs are recruited in order of size from small to large (Petajan, 1991). Typically, small MUs are type I units, and unit size increases with progression through the fiber types: type I < type IIA < type IIB. Therefore, when low force is required, only type I MUs will be active. Only when force or power is high will recruitment demand involvement of the larger MUs (MacIntosh et al. 2006). The relative contributions of recruitment and firing rate of MU to the force exerted by a muscle vary with the level of muscle force and the muscle performing the task. In most muscles, the upper limit of MU recruitment is ~75% of the maximal force (De Luca et al. 1982; Kendall et al. 2006). The increase in muscle force beyond the upper limit of MU recruitment is accomplished entirely by increase in MU firing rate (Duchateau et al. 2006).

The electromyogram (EMG) is a reflection of MU action potentials within an active muscle. Changes in EMG pattern are usually attributed to changes in the number of recruited MUs and/or changes in their excitation frequency, although changes in conduction velocity or the level of MUs' synchronization may also play a role (Finsterer,

2001; Bigland-Ritchie et al. 1986). While it may be difficult to distinguish between the factors that contribute to the EMG pattern, changes in the latter reflect changes in neuromuscular function. Additionally, the EMG pattern of muscles can be influenced by age, sex, the degree of voluntary and involuntary muscle contraction, temperature, fatigue, and fitness level. Moreover, recording conditions like recording site, electrode type, filter setting, sampling frequency greatly influence the EMG pattern and should be taken into account (Finsterer, 2001).

Some studies suggest that part of the strength differences between children and adults may be due to neurological changes that occur during growth. That is, the fact that voluntary strength increases proportionately more than the increase in anthropometric parameters, suggests that muscle strength may depend not only on the muscle size, but also on the extent to which it is activated (Grosset et al. 2008; Belanger & McComas, 1989).

A few studies using the interpolated twitch technique reported an almost complete activation of MUs in the triceps surae and quadriceps muscles in children during MVC (Belanger & McComas, 1989; Blimkie et al. 1990). However, a note should be made that in a recent study Kendall et al. (2006), suggested that the use of interpolated twitch technique, in order to measure muscle activation might overestimate the extent of neural activation during MVC. The authors used MRI analysis to measure muscle activation during MVC and demonstrated that only 75% of the muscle was activated during maximal voluntary effort, while the interpolated twitch technique indicated over 90% muscle activation during the same type of contraction. The authors suggested that the results of previous studies using the latter technique should be interpreted with caution.

In line with Kendall et al.'s (2006) findings, Davies (1985) reported only 78% MU activation during maximal voluntary knee extension in children. Similar findings were reported by Ramsay et al. (1990). This was supported by Paasuke et al. (2000) who compared electrically evoked twitch contraction characteristics of the plantar flexor muscles in boys and men. The authors found that pre-pubertal boys had significantly higher ratios of twitch peak torque to MVC compared to post-pubertal boys and men. Based on those results, they concluded that adult men were able to activate a greater percentage of their available MUs when compared with pre-pubertal boys. Grosset et al. (2008), using the interpolated twitch technique demonstrated that younger children (age 7 yrs) had a higher activation deficit when compared with older children (9-11 yrs) and adults. Activation deficit was considered as the torque achieved during the interpolated twitch over the torque value just before the electrical stimulation. Using the same technique, Blimkie (1989) found that the percentage of MU recruitment in boys increased with age in the knee extensors. This increase could not be demonstrated for the elbow flexors, possibly due to the great variability of the results. Nevertheless, the above studies suggest an activation pattern, which changes with growth and maturity. All the cited studies have examined the extent of muscle activation in children with a comparison to adults. However, none of those studies have examined the rate of rise in muscle activation, as reflected by the rate of increase in EMG (Q_{30}) activity and whether age-dependent differences exist.

Due to the differences in the contractile properties of fast and slow muscle fibres in skeletal muscles, differences in muscle fibres recruitment may also account for the observed differences in RTD between children and adults. For example, both Asai &

Aoki (1996) and Falk et al. (2009b) reported lower RTD in pre-pubescent boys compared with adults. Asai & Aoki (1996) suggested that the recruitment and changes in firing rate of MUs on the basis of the size principle might not be well established in children, which may explain the observed differences between the two age groups. Falk et al. (2009b) have also suggested that the lower RTD in children may be due to their lesser recruitment and utilization of the faster, higher-threshold MUs. This is supported by Halin et al. (2003), who reported that during 30-s of isometric elbow flexion MVC, force decrement was lower and the decline in the EMG mean power frequency was lower in boys than in men. Based on these findings, the authors suggested that the boys' lower maximal strength and fatigability were due to lower involvement of type-II muscle fibres. Only Falk et al. (2009b), have related the rate of muscle activation (Q_{30}) to RTD. The authors suggested that even when muscle activation was taken into account, peak RTD absolute or corrected for peak torque, remained lower in boys. They suggested that although muscle activation might play an important role in the age-dependent differences in RTD other factors may also be involved in determining the RTD.

Lastly, previous investigators also suggested that the neuromuscular system is still maturing with respect to the myelination of the nerves in younger children. Garcia and others (2000) demonstrated that motor neuron conduction velocity, sensory neuron conduction velocity, and the amplitude and morphology of action potentials increase during the first year of life. In this study, maximal conduction velocities were twice as fast in adults as in neonates. However, values of all these measures approached adult levels by age four or five years.

On the other hand, muscle fibre conduction velocity has been seen to increase with age in children (Malmstrom & Lindstrom, 1997) and might also play a role in the observed age-related strength differences (Halin et al. 2003).

2.2.5 Co - Activation

Another factor that can affect muscle strength is co-activation of antagonist muscle groups. Co-activation may be defined as the simultaneous activation of agonist and antagonist muscles during the execution of a task (Frost et al. 1997). It has been suggested that the functional significance of antagonist activation may be a protective response of the central or peripheral nervous system to stabilize the joint and protect it from injuries (Kellis & Unnithan, 1999). Gabriel et al. (2001) proposed that during maximal elbow flexion, triceps brachii coactivity plays a major factor in stabilizing the joint. In a circumstance where triceps brachii coactivity is insufficient to stabilize the elbow joint, biceps brachii activity will be suppressed in order to prevent injury.

In situations of increased antagonist muscle activation beyond the level necessary for joint stability, peak force production might be affected. For example, Stackhouse et al. (2005) examined the differences in muscle activation between children with and without cerebral palsy, and reported the former to have higher antagonist co-activation, which may contribute to their lower peak force.

Inconsistencies in the literature exist regarding co-activation patterns in children and adults. Those might be attributed to different modes of contraction and to the different muscle groups tested. For example, co-activation is naturally higher in dynamic contractions relative to isometric contractions (Folland & Williams, 2007). Additionally, as suggested by Kellis & Unnithan (1999), the lower extremities muscle groups (e.g.

quadriceps and hamstring) are actively involved in habitual activities. This may result in a more efficient use of these muscle groups compared with muscles of the upper extremities and may lead to lower co-activation levels in the lower extremities.

During dynamic submaximal contractions, such as walking and running, younger children (7-8 years) exhibit higher levels of co-activation compared with older children (15-16 years) (Frost et al. 1997). During isokinetic movements of knee flexion and extension, on the other hand, Kellis & Unnithan (1999) and Bassa et al. (2005) noted no age-dependent difference in antagonist co-activation.

During isometric contraction of the plantar flexors, Lambertz et al. (2003), found a trend toward an age-related decrease in co-activation in 7 to 11 year old children compared with adults. However, Morse et al. (2008) did not demonstrate any child-adult differences in co-activation during isometric contractions in the same muscle groups. This was supported by Falk et al. (2009a,b), who reported no age-related differences in co-activation index during execution of maximal isometric elbow flexion and extension.

2.2.6 Elasticity of the muscle-tendon unit

The elasticity of the muscle-tendon unit may play a role in the observed differences in RTD and electro-mechanical (EMD) between children and adults. Findings obtained from animal and human cadavers have shown age-dependent changes in elastic properties of tendons. With growth, the tendons become stronger, stiffer and less extensible (Nakagawa et al. 1996; Shadwick, 1990).

The elastic properties of tendon structure influence the transmission of the force exerted by the muscle fibres to the bone (Fukunaga et al. 1997). Thus, the tendon

structures and their compliance would affect the RTD and the response of the stretch reflex (Going et al. 1987; Wilson et al. 1994; Narici et al. 1996).

Kubo et al. (2001) found that the elastic properties of the vastus lateralis tendon structures were more compliant in young boys (10 yr) compared with adolescent boys (15 yr) and adult men (24 yr). No differences were found between the adolescent and adult group, suggesting that the tendon structure is not changing in a linear fashion. The authors suggested that the more compliant tendon structures in children should make the RTD lower compared with adults.

In skeletal muscle contraction, a delay exists between the onset of electrical activity and measurable tension. This delay is called the electromechanical delay (EMD) and it has been stated to be between 30 and 100 ms (Cavagna & Komi, 1979). It is thought to reflect the time necessary for contraction of the contractile component and stretching of the series elastic component (Asai & Aoki, 1996), but other factors can also affect it. These include conduction of the action potential along the T-tubule system, release of calcium by the sarcoplasmic reticulum, and cross-bridge formation between actin and myosin filaments (Cavagna & Komi, 1979).

Few studies have investigated the differences in EMD between children and adults. Both Asai & Aoki (1996) and Falk et al. (2009b) observed a significantly longer EMD in the elbow flexors muscles in children when compared with adults. Falk et al. (2009b) also found the same pattern during elbow extension. In another study, which compared the triceps surae twitch contractile properties in prepubertal children (7 to 11 y), Grosset et al. (2005) found that EMD values decreased with age, but still remained higher than those of adult subjects. The authors suggested that the higher EMD values

found for prepubertal children and the age-dependent changes of this parameter give indications concerning an increase in musculotedinous stiffness in this age range. However, Cornu & Goubel (2001) could not demonstrate such a difference during elbow flexion. Furthermore, Grosset et al. (2009) reported that musculo-tendinous stiffness changes could only account for about 20% of the variance in EMD changes. Thus, other possible determinants account for the longer EMD reported in children such as: lower muscle activation, however the latter was not examined. The author is unaware of any studies that have examined the difference in EMD during knee extension and flexion.

2.2.7 Muscle architecture

Skeletal muscle force production is influenced by a muscle's size and architecture (arrangement of muscle fibres) (Kawakami et al. 2006). There has been speculation that the angle of muscle pennation plays a role in the age-differences in strength. The greater the angle of pennation of the muscle, the smaller the proportion of force in the muscle fibres that is transmitted to the muscle tendon and the lower the measured external force (Blimkie, 1989; De Ste Croix, 2007). There is limited evidence that the muscle's pennation angle may increase with age (Blimkie, 1989). The lower angle of pennation actually provides children with biomechanical advantage compared with adults. Nonetheless, the importance and effect of these changes in pennation for strength development during growth is still unknown, and it appears to have a minor role in the observed strength differences between children and adults (Rowland, 2005).

2.3 Neuromuscular Adaptations to Training

Regardless of growth and maturation factors, adaptive alterations in maximal contraction force and power as well as maximal RTD can also be a response to specific types of training. Skeletal muscle has the ability to adapt to the circumstances of its use. Physical training of a movement or task will lead to the enhancement of performance of that task. Endurance training usually increases a muscle's resistance to fatigue by inducing increases in mitochondrial numbers and volume, and oxidative enzyme activity (Holloszy & Booth, 1976). On the other hand, heavy resistance training results in enhanced strength due to muscle fibre hypertrophy, primarily by disproportionate increases in contractile proteins relative to sarcoplasmic constituents (MacDougall et al. 1982).

The neuromuscular system develops from birth through adulthood. Therefore, it is likely that training induces specific alterations in neuromuscular control depending on the nature and intensity of training (Bencke et al. 2002) and maybe also depending on the developmental stage during which training takes place (Rowland, 2005). The following pages discuss only the neuromuscular adaptations to endurance training in both, adults and children.

2.3.1 Endurance training and muscle performance in adults

Numerous studies in adults have examined the neuromuscular adaptations to different types of training. De Luca et al. (1982) suggested that during contraction, there appears to be a functional reserve of MUs. These MUs are presumably not readily available and part of the increased MU activity following training may be related to "learning" to fully activate some of the MUs that were not previously active. This is

supported by other studies which reported that humans are unable to fully activate muscle voluntarily (Dowling et al. 1994; Knight & Kamen, 2001), but that training improves activation.

In adults, typical resistance training with high loads results in neural and muscle hypertrophic adaptations responsible for improved strength of the trained muscles (Hakkinen et al. 2003). On the other hand, the effect of endurance training on strength and neural adaptations is unclear. Most of the studies on adults have examined the molecular, biochemical, cardiac and metabolic adaptations to endurance training. Those studies have shown that endurance training results in a change of physiological, biochemical and structural features of mainly type II fibres (Howald et al. 1985; Simoneau et al. 1985; Thayer et al. 2000). Those changes cause type II fibres to acquire the features which are typical of type I fibres. Furthermore, some studies have shown that type IIb, may convert to type IIa and even type I (MacIntosh et al. 2006). Short et al. (2005) found that in response to a 4 months endurance exercise training, there was a general shift from fast to slow myosin heavy chain (MHC) isoform expression. MHC I and IIa mRNA increased, while IIx decreased. There is a paucity of data in adults on the effect of endurance training on maximal strength, rate of muscle activation (Q_{30}), RTD and EMD.

Several cross-sectional studies compared the effects of power and endurance training on maximal strength. Those studies have used different instruments to measure maximal strength and power, therefore a comparison between the studies is challenging. Nevertheless, it is well established that endurance-trained athletes have lower maximal strength compared with power athletes (Izquierdo et al. 2002; Sleivert et al. 1995; Ullrich

& Bruggemann, 2008; Lattier et al. 2003; Kyrolainen & Komi, 1994). However, conflicting evidence exists regarding the differences in maximal strength between endurance-trained athletes and sedentary individuals. While some cross-sectional studies (Sleivert et al. 1995; Kanehisa et al. 1997), and training studies (Hickson, 1980; McCarthy et al. 2002; Grandys et al. 2008), reported no difference between the two populations in maximal strength, other studies reported endurance athletes to be stronger than their untrained counterparts (Izquierdo et al. 2002; Lattier et al. 2003). These discrepancies could be possibly attributed to different types of contractions tested, different equipment used, and training levels and backgrounds of the athletes.

Differences between athlete populations are attributed to the emphasis of training, typical for each sport as well as differences in muscle fibre composition prior to training. For example: Izquierdo et al. (2002) mentioned that the weightlifter and handball players tested in their study usually engaged in resistance and power training, whereas the cyclists and the runners engage mainly in endurance training, with little or no resistance training. However, in the same study the elite road cyclists (endurance athletes) were stronger than the untrained controls. The authors attributed those differences to a possible training adaption. Typical cycling training and competition's intensities involve submaximal intensities interspersed with short bursts of high power, which could possibly affect the fibre-type recruitment in those athletes, and may improve neural activation and intrinsic muscle qualities. This hypothesis was supported by (Lattier et al. 2003; Lucia et al. 2000). In a cross-sectional study, Lattier et al. (2003) compared the explosive and isometric strength of endurance-trained, power-trained and sedentary subjects. The authors found that endurance-trained athletes had higher maximal isometric

force and maximal voluntary activation of knee extensors than sedentary subjects. The authors suggested that these results demonstrate neural adaptations (e.g. maximal voluntary activation), due to any given type of training, regardless of the intensity of the training stimulus.

Furthermore, in order to investigate the effect of endurance training on the neuromuscular system, Lucia et al. (2000) conducted a longitudinal study on professional cyclists, analyzing the changes in metabolic and neuromuscular variables induced by endurance training during a full sports season. Surface electromyography (SEMG) recordings were obtained from the vastus lateralis muscle to determine RMS-EMG amplitude (root mean square) and mean power frequency (MPF). Their main finding was that endurance training resulted in a lower circulating lactate at sub-maximal intensities and a possible increased reliance on oxidative metabolism. Interestingly, it also resulted in increased RMS-EMG during the training season, which the authors attributed to enhanced recruitment of motor units in the active muscles. Furthermore, MPF values tended to increase from resting period to pre-competition and decrease during the competition period. The authors suggested that as the volume of low-to-moderate intensity training increases (from rest to pre-competition), a greater number of MUs firing at fast frequencies are recruited in the active muscles of elite endurance athletes. However, further into the training program (competition period), more demanding training loads are taken. During this time, firing frequency showed a considerable decrease. This finding might be attributed to a further improved ability to recruit additional slow motor units (type I fibres) which are characterized by lower frequencies. Given the fact that exercise lactate levels decreased while VO_2 values remained

unchanged throughout the season, the authors hypothesized that these additional MUs are mainly composed of slow (type I) muscle fibres. This hypothesis is corroborated by the lactate data, which show lower levels during the competition period suggesting reduced glycolytic metabolism (greater involvement of type I fibres). Similar findings were reported by Cafarelli et al. (1995), who trained young adults in 8 weeks of single-leg endurance training on a cycle ergometer.

The above findings are further supported by studies, which examined the twitch contractile properties of plantar flexors muscles among endurance and power trained athletes and untrained subjects. Paasuke et al. (1999) have reported that power-trained athletes had higher absolute twitch maximal force, maximal RTD and MVC compared with the other two groups. No relative comparison (e.g. size adjusted) was made between the groups. Several factors could have contributed to the observed differences. First, power trained athletes have larger muscle cross-sectional area, which may be associated with their higher MVC. Secondly, power-trained athletes have greater percentage of fast twitch fibres in their muscles compared with endurance-trained athletes (Costill et al. 1976), which may contribute to the higher RTD and to their higher MVC. Thirdly, changes in excitation-contraction coupling and contractile properties of the muscle fibres, neural adaptation (increased MU activity, improved MU synchronization), were also suggested as possible mechanisms for those differences (Paasuke et al. 1999). This was supported by Maffiuletti et al. (2001) who suggested that endurance-trained athletes had a higher preferential activation of slow twitch units compared with power athletes and untrained control subjects. Although a small number of studies have looked at the effect

of endurance training on the neuromuscular system, none of those studies have investigated the effect of endurance training on the rate of muscle activation (Q_{30}).

Elliot et al. (2007) in their review suggested that the additional recruitment of slow-twitch fibres and resultant decrease in the percentage of fast-twitch fibre cross-sectional area in endurance-trained athletes could compromise strength and speed capabilities. However, as it was previously stated in this section, some studies have reported that muscle strength in athletes, even endurance-trained, is greater than non-athletes (Lattier et al. 2003). Another possible explanation for the greater maximal strength displayed by athletes (Lattier et al. 2003; Carolan & Cafarelli, 1992), is a training-induced reduction in co-activation. This has been demonstrated following resistance training (Carolan & Cafarelli, 1992; Hakkinen et al. 1998), but may also occur following endurance training. In fact, Osternig et al. (1986) reported lower co-activation in long distance runners compared with sprinters during knee extension. However, co-activation level of long distance runners was found to be similar to that of untrained individuals (Osternig et al. 1986; Westing et al. 1991).

The effect of endurance training on RTD has been studied to a lesser extent. A lower rate of force production in endurance-trained compared with power-trained athletes has been reported during knee extension (Sleivert et al. 1995; Ullrich & Bruggemann, 2008, Kyrolainen & Komi, 1994; Hakkinen & Keskinen, 1989) and plantar flexion (Sleivert et al. 1995; Kyrolainen & Komi, 1994). This difference between athletes may be the result of training but may also be a result of different muscle fibre composition, differences in muscle mass and differences in neural activation. Only one study has compared endurance athletes to untrained subjects (Sleivert et al.1995). The authors

reported no differences in RTD between the two groups. However, RTD was presented in absolute values and no relative comparison was made.

Changes to the muscle-tendon unit due to endurance training have been reported in a few studies (Woo et al. 1981; Kubo et al. 2000). Kubo et al. (2000) examined the changes that occurred to the elastic properties of muscle tendon complex in long distance runners. They found that compared to a non-athletic control group, the muscle-tendon complex of the vastus lateralis was less compliant, which can help transmit the force from the muscle to the tendon more effectively and can help perform brisk, accurate movements. The authors suggested that the mechanical stress imposed on the tendon as a result of the running training may result in changes to the tendon structure such as, an increase in the number, diameter and degree of alignment of the constituent collagen fibres. The lower muscle-tendon compliance in the athletes could possibly affect RTD and resulted in a shorter EMD, as suggested by Grosset et al. (2009).

It should also be mentioned that all the above cited studies have been conducted on the lower extremities, mainly the knee extensors and plantar flexors muscle groups. No studies have looked at the effect of endurance training on the upper extremities muscle groups.

2.3.2 Endurance training and muscle performance in children

Studies which examined the possible effects of endurance training in children focused mainly on metabolic and cardiovascular adaptations (Baquet et al. 2003; Eriksson et al. 1973). None have examined the effect on neuromuscular function. While resistance training is believed to increase muscle strength and power by inducing neuromuscular adaptations in children and adolescents (Blimkie, 1992; Malina, 2006),

there are no comparable studies on endurance training in children. Furthermore, there are no studies in children examining the effect of any type of training on co-activation, EMD and RTD.

2.4 Summary

Children gain strength as they get older mainly due to changes in body dimensions (mass, stature, mCSA). Nevertheless, there is evidence that children gain strength more than can be explained by the increase in body size. Therefore, it was suggested that other factors play a role in the observed changes in muscle performance from childhood to adulthood. These factors include changes in hormonal levels, muscle composition, muscle activation patterns, co-activation pattern, elasticity of the muscle-tendon unit and muscle architecture.

An important factor explaining some of the child-adult strength differences may be the neuromuscular function. Muscle activation plays an important role in muscle strength and performance, and differences in muscle activation pattern (number of recruited MUs and/or changes in their excitation frequency) may be partially responsible for the force production differences observed between children and adults. Nevertheless, the role and the extent to which muscle activation plays a role in muscle performance development in children are still unclear.

There is limited information on MU activation in children. Some authors suggest that adult men can activate their muscles to a greater degree than pre-pubertal boys, possibly reflecting higher type II fibre recruitment. This is supported by the lower RTD reported in boys compared with young men. Moreover, during isometric contraction, boys are reported to have longer delays between the onset of electrical activity and that of

measurable tension (EMD). It is suggested that the higher EMD in children is related to a lower RTD.

Lastly, although endurance training may induce neuromuscular adaptations in adults, there are no known studies to date which describe neuromuscular adaptations following endurance training in children. In adults, from the limited data in the literature, it appears that endurance training increases neuromuscular activation, mainly of type I MUs, and possibly increases maximal strength. Whether this pattern exists in children remains unclear.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Research Design

In this study, a cross sectional design was used to address the question of whether endurance training affects muscle performance and neuromuscular function and whether this effect is already evident during childhood. Surface electromyography (sEMG) and an isokinetic dynamometer system were used to compare endurance-trained boys and endurance-trained adult athletes with aged-matched non-athletic males. The study and its procedures received ethics approval by the Brock University Research Ethics Board (file # 05 - 155).

3.2 Study Sample

The study sample included four groups:

a. Muscle-endurance-trained boys (swimmers) (7-11 yrs) who have been actively involved in their sport for at least 1.5 years and trained at least 6 hr/wk.

b. Untrained boys (7-11 yr) who have not been actively involved in any form of regular physical training ($\leq$ 2/wk).

c. Young muscle-endurance-trained men (swimmers/triathletes) (18–35 yrs), who have been actively involved in their sport on average 6.4 $\pm$ 4.3 yrs and train at least 6 hr/wk.

d. Young untrained males (18–35 yrs) who have not been actively involved in any form of regular physical training ($\leq$ 2/wk).

Control subjects were recruited from St. Catharines area and Brock University through flyers (Appendix A) and information sessions. The endurance athletes were recruited from the Golden Horseshoe area, through swimming and triathlon clubs.

The endurance-trained participants were highly trained athletes who trained year-round in a structured swimming or triathlon program (The adult group consisted of seven triathletes and eight swimmers, while the children group consisted of swimmers only). The adult athletes specialized in middle and long distances events (200-1500m). Six endurance-trained men participated in their sport at a top national level. Six endurance-trained men participated in a university varsity swimming program. Three endurance-trained men were regional competitive triathletes. Seven boys competed at a provincial level, while five boys participated at regional level. It should be noted that the endurance capacity of the endurance-trained athletes was not measured. Both the men and the boys participated in a structured resistance-training program in addition to their endurance-training program (2.5 ± 1.3 hr/wk, and 3.4 ± 1.5 hr/wk, respectively).

All the boys were classified as pre-and early-pubertal based on (Tanner, 1962) sexual maturation.

Those subjects who had prior or present condition that could affect muscle or neuromuscular function (e.g muscular disease, use of medications, and injury to dominant hand/leg) were excluded from the study. Boys who reported to be stage III or higher in sexual maturation (Appendix G) were excluded as well.

3.3 Procedure

All tests and measurements were performed during two visits to the Musculoskeletal Assessment Lab at Brock University, between July 2008 and April 2009. Prior to the first visit to the lab, the participants were contacted via phone or email and instructed to refrain from exercise the day preceding the testing.

On the first visit, subjects were informed of the purpose, methods, and potential risks of the study. Before testing, an informed consent form was signed by the participant or by the children's parents (Appendix C). Once arrived to the lab, anthropometric measurements (mass, height, sitting height, skinfold thickness, limb's length and circumference), muscle depth using ultrasound were assessed, and questionnaires (medical, physical activity, pubertal stage) were filled out. Subjects then performed a shorter version of the testing protocol in order to become familiar with the instructions, equipments and the testing procedure. The initial setting on the dynamometer was individually adjusted and the position of all dynamometer attachments was recorded in order to be used during the second visit. On the second visit, subjects performed only the strength testing protocol.

3.4 Measurements

3.4.1 Anthropometric measurements (See Appendix F)

Height and body mass were measured using an Ellard Instrumentation board length stadiometer (Monroe, WA, USA) and a digital scale (Zenith), respectively with subjects in light clothing and no shoes. Both height and body mass were recorded to the nearest 0.1 cm and 0.1kg, respectively. Sitting height was also recorded in order to estimate the age of peak height velocity, reflecting somatic maturity (Mirwald et al. 2002).

Skinfold thickness was measured in triplicate using Harpenden calipers (British Indicators, Herts, England) and the median value at each site was used. The following sites were evaluated: biceps, triceps, subscapular and suprailiac. Adiposity (percentage of body fat) was estimated from the appropriate skinfold measurements, using age- and

maturity-specific equations (Slaughter et al. 1988; Durnin & Wohmersley, 1974). The coefficient of variance (CV) of this measurement was 5% and the intra-class correlation coefficient in 10 subjects was $r = 0.98$.

In addition, skinfolds thickness of anterior, posterior, medial and lateral thigh was determined in order to estimate muscle cross sectional area (Gurney & Jelliffe, 1973). Circumference and length of the upper arm and thigh were determined using standardized methods (Lohman et al. 1988). Upper arm length was measured from the acromion process of the scapula to the lateral epicondyle of the humerus. The thigh length was measured from the greater trochanter of the femur to the lateral condyle of the femur as reported previously (Abe et al. 1994). Upper arm cross-sectional area was calculated using measures of upper arm circumference as well as biceps and triceps skinfold thickness, as previously described (Gurney & Jelliffe, 1973). The same investigator carried out all anthropometric measurements. The intra-class correlation coefficient of the muscle cross sectional calculation was $r = 0.99$ for the thigh and $r = 0.99$ for the arm. The CVs of these measurements were 4% and 2%, respectively.

3.4.2 Pubertal stage

Pubertal status was determined using secondary sexual characteristics (pubic hair), as described by (Tanner, 1962). Pubertal stage was self-reported, using drawings (Duke et al. 1980) (Appendix G). The self-assessment form was placed in an envelope by the subject and handed directly to the researcher, to assure discreetness.

3.4.3 Muscle depth (diameter)

Muscle depth was measured using a real-time B-mode ultrasound (System5, GE Vingmed, Horten, Norway) with 5 MHz linear-array probe. Sagittal images of the biceps

brachii, triceps brachii, quadriceps muscles, and biceps femoris were obtained at rest while the subject was lying supine on a bed. The anthropometric location of the sites was performed by the same investigator before the ultrasonic measurements. For the biceps brachii and triceps brachii the measurements were taken on the anterior and lateral surface 60% distal between the lateral epicondyle of the humerus and the acromion process of the scapula. For quadriceps and hamstrings the measurements were taken on the anterior and posterior surface midway (50%) between the lateral condyle of the femur and greater trochanter (Abe et al. 1994).

The scanning head of the probe was oriented along the mid-sagittal and transverse axis of each muscle. A water-soluble transmission gel was applied over the scan head to improve the ultrasound image. Three to four measures were taken in each site, recorded on a computer and analyzed off-line. Muscle depth was measured as the distance between the adipose tissue-muscle interfaces to the muscle-bone interface. The median value was used for analysis. The same investigator carried out all ultrasonic measurements. Muscle cross sectional was calculated from the muscle depth, using the following formula: CSA = $(\text{Muscle depth}/2)^2 * \pi$. The intra-class correlation coefficient of the muscle depth in 10 subjects was $r = 0.91$ for the biceps brachii, $r = 0.90$ for the triceps brachii, $r = 0.97$ for the hamstrings and $r = 0.98$ for the Quadriceps. The CVs of these measurements were 9.9%, 8.7%, 4.3% and 7.6%, respectively.

3.4.4 Questionnaires

Questionnaires were completed by the subject, if needed with the help of the investigator and possibly parent, to assess subject's medical history (Appendix D), physical activity levels and training history for the athletes. Physical activity level was

assessed using a standardized questionnaire (Godin & Shepherd, 1985) (Appendix H), as well as by a personal interview. Past and present training experience was self-reported, through a personal interview (Appendix I).

3.5 Strength Testing Protocol

An isokinetic dynamometer system (Biodex III, Biodex, Shirley, NY) was used to measure isometric strength (torque) of the elbow and knee flexors and extensors of the dominant arm and leg, respectively (Appendix E). The Isokinetic dynamometer system was found reliable for measuring muscle strength in children and adults (Dvir, 1995). A similar protocol was used in previous studies in the pediatric and adult population in our lab (Falk et al. 2009a,b). In order to reduce the noise on the recorded torque channel, an EMG/analog signal access interface (Biodex, Shirley, NY) was used. This utility configures the scale factors of the analog signal outputs for torque. For each participant the scaling factor was adjusted according to the torque values reached in the habituation session during the first visit.

For the upper limbs, subjects sat upright in a chair with the shoulder at 90° of flexion, upper arm resting on an arm rest adjusted for the subject's height. The subject's elbow was placed at 90° of flexion and the hand was in neutral position. The torque axis was positioned in alignment with the lateral humeral epicondyle. After adjustments, subjects were secured in the chair to prevent stabilizing movements that could affect the measurements with two straps secured across the chest in an X fashion and a hip strap to stabilize the trunk.

For the lower limbs, subjects sat upright in a chair with hip angle of 120°, and the knee at 90° of flexion. The ankle was secured (using Velcro straps) to an adjustable lever

arm. The torque axis was aligned with the lateral femoral epicondyle. After adjustments, subjects were secured in the chair to prevent stabilizing movements that could affect the measurements with two straps secured across the chest and another strap across the thigh.

The testing protocol included four type of contractions in which the subjects performed three sets of five 3-seconds repetitions. A 30-seconds rest followed each repetition. Rest between each set was 2 minutes. The order of the sets (flexion/extension, upper/lower limb) was counterbalanced between subjects. The first set for each type of contraction served as a specific warm up, the subject performed a set of five voluntary contractions in a progressive manner; from very light contraction up to maximal contractions. Then the subject performed two sets of five 3-seconds repetitions of maximal voluntary contraction (MVC). Additional sets were added as needed to reach at least 5 valid MVCs if some data were deemed unacceptable due to execution errors, deviations in EMG baseline, or abnormal torque or EMG amplitudes or tracing. Each subject was instructed to contract "as hard and as fast as possible" from a relaxed state to ensure maximal torque and RTD. Subjects were verbally encouraged to perform a maximal effort throughout each contraction. Online visual feedback of the dynamometer's force signal was available for the subjects on a PC screen. Visual feedback has been shown to be important for torque production (Kellis & Baltzopoulos, 1996), especially in young children (Smits-Engelsman et al. 2003). During the isometric MVC in each set, peak torque was recorded from the dynamometer system and sEMG signals were recorded from the agonist and antagonist muscles.

3.6 Electromyography (EMG)

3.6.1 Electrode placement

During the isometric MVC in each set, EMG signals were collected from the agonist and antagonist muscles using bipolar surface electrodes (Delsys 2.1, Delsys Inc., Boston, MA).

In the upper limbs, electrodes were placed on the muscle belly midsections of the biceps brachii and the lateral head of the triceps brachii. In the lower limbs, electrodes were placed on the muscle belly of the vastus lateralis and biceps femoris. These were determined visually during a resisted static contraction. The electrodes were placed in line with the muscle fibres away from the estimated motor point (Delagi & Perotto, 1980). A ground electrode served as a reference electrode and was placed over the clavicle.

In order to reduce impedance, electrode sites were prepared by shaving the relevant area when necessary, thoroughly rubbing the skin with abrasive gel, and cleaning with alcohol, before placing the electrodes. The same investigator performed all electrode placements.

3.6.2 Technical information

The SEMG activity was recorded with Delsys 2.1 (Delsys Inc., Boston, MA) bipolar surface electrodes, band-passed filtered (20-450 Hz) using the Bagnoli-4 (Delsys Inc., Boston, MA) bioamplifier. All signals were sent to a 16-bit A/D converter (BNC-2110, National Instruments) and sampled at a rate of 1000Hz using a Computer-Based Oscillograph and Data Acquisition System (EMGworks). Recorded data were stored for further analysis.

3.7 Data Reduction and Analysis

Using EGGLAB and MatLab (The MathWorks, Natick, MA), several variables were calculated for each type of movement tested.

Mean traces of the best five trials of EMG agonist, EMG antagonist and torque were created in order to reduce signal-to-noise ratio. Torque and EMG traces in each set were visually examined and the best five repetitions to be averaged were chosen based on the following criteria: clean EMG baseline prior to the beginning of the recording, clear RTD, clear onset of torque and EMG activity. Any faulty trials were eliminated and out of the remaining repetitions, the best five repetitions were used for analysis, based on the highest peak torques and RTD values. In a limited number of cases (Elbow flexion: five control boys and two endurance-trained boys; Elbow extension: four control boys and one endurance-trained boy; Knee flexion: one control boy), less than five trials were averaged, due to the quality of the signal recorded.

The mean traces were used to calculate peak torque, RTD, rate of rise of muscle activation (Q_{30}), electromechanical delay (EMD), time to peak torque, time to peak RTD and co-activation. Peak RTD was calculated by taking the maximum of the 1st derivative of the torque signal (Gabriel et al. 2001). Agonist and antagonist amplitudes were calculated from the detected linear envelope. The peak EMG amplitudes values were taken 250ms around the peak torque latency. Rate of muscle activation (Q_{30}) was measured over the first 30ms of electromechanical activity. Q_{30} was defined as the area under the EMG curve of the linear envelope of the detected EMG signal during the first 30 ms (Gottlieb et al. 1989; Gabriel & Boucher, 2000). Electromechanical delay (EMD) was defined as the delay (ms) between the agonist EMG activity onset and the onset of

torque production. The EMG activity onset was defined as the point in time at which the rectified linear envelope EMG rose above the 95% confidence interval for baseline noise and stayed above that point for more than 20 msec. The onset of torque was defined as the point in time in which the torque linear envelope rose above the 95% confidence interval for baseline noise of the RTD channel and stayed above that point for more than 10 msec. The time to peak torque was calculated as the time delay (ms) between the onset of torque generation and the occurrence of peak torque. The time to peak RTD was calculated as the time delay (ms) between the onset of torque generation and the occurrence of peak RTD. Co-activation was calculated as the ratio between the antagonist's EMG amplitude divided by its EMG amplitude as an agonist (i.e., for knee extension: [Biceps femoris EMG amplitude in knee extension] / [Biceps femoris EMG amplitude in knee flexion].

3.8 Statistical Analysis

All statistical analyses were performed using SPSS (SPSS Inc., Chicago, IL). The data for all groups are presented as mean (M) $\pm$ standard deviation (SD). The data were cleaned by checking for outliers (> 2 standard deviations from the mean) of all dependent variables (Appendix J-M) for each of the four contractions. A Chi square analysis was used to compare the pubertal stage distributions. Group differences in muscle performance and neuromuscular function were determined using a two-way analysis of variance (ANOVA), with training (untrained, endurance) and age (children, adults) as the between-subjects main effects. Post hoc comparisons (LSD) were performed when a main effect or interaction was found to be statistically significant. Pearson correlation coefficient was calculated to examine the relationship between dependent variables. Each

contraction was analyzed separately. Subsequently, all contractions were analyzed together using Two-way ANOVA for repeated measures to identify general patterns. The acceptable level of significance was set at $p < 0.05$.

CHAPTER 4: RESULTS

Forty five boys and thirty five young men volunteered to participate in the study. Five boys were excluded because they reported to be stage III in sexual maturation. Eight boys reported participating in less than 6 hours of structured swimming training per week and were consequently excluded from the data analysis. Two boys did not complete the second session of testing. Therefore, a total of 65 participants were included in data analysis: 30 boys and 35 men.

The physical characteristics of the subjects are displayed in table 4.1. The men were older, taller, and heavier than the children. There was no significant difference in age between the untrained control boys and the endurance-trained boys groups as well as between the untrained control adult and the endurance-trained adult groups. There was no difference in height within age groups. There was an age-by-training interaction for body mass, reflecting the fact that among the boys, the endurance-trained boys were heavier, while among the adults, the pattern was reversed. The men also had significantly greater lean body mass and arm and thigh CSA and muscle depth, compared with the boys. There were no significant differences between and within the age groups in body fat percentage. There were no significant differences in sexual maturation stage between the two boys groups. However, years from age of PHV were significantly different between groups, with athletes being somatically more mature (Table 4.1).

There was a significant difference in training hours between the trained groups. The endurance-trained adults trained 14.4 $\pm$ 5.0 hr/wk on average while the endurance-trained boys trained 8.5 $\pm$ 3.6 hr/wk.

Data for all four types of contractions (elbow flexion and extension, knee flexion and extension) were collected. Since the pattern of results was similar in all four types of contractions, for the purpose of simplicity only knee extension data are presented within the text. All data appear in appendices N-AA.

Table 4.1: Physical characteristics of the endurance-trained and untrained boys and men

	Children		Adults		
	Control (n=18)	Endurance (n=12)	Control (n=20)	Endurance (n=15)	**Effect**
Age (yrs)	9.9 ± 1.3^{a}	10.7 ± 0.7^{b}	22.8 ± 4.4^{a}	24.5 ± 5.9^{b}	A
Tanner (I,II,III,IV,V)	11,7,0,0,0	7,5,0,0,0	-	-	
Years from Peak Height Velocity	-3.3 ± 0.9^{a}	-2.5 ± 0.7^{a}	-	-	T
Height (cm)	140.3 ± 9.1^{a}	145.9 ± 7.2^{b}	180.5 ± 7.4^{a}	179.2 ± 5.7^{b}	A
Weight (kg)	$34.9 \pm 8.1^{a,c}$	$41.5 \pm 12.6^{b,c}$	$80.4 \pm 12.4^{a,d}$	$74.7 \pm 6.0^{b,d}$	A, A*T
Arm CSA (cm^2)	28.1 ± 6.8^{a}	35.2 ± 9.1^{b}	68.3 ± 11.2^{a}	67.4 ± 7.1^{a}	A
Thigh CSA (cm^2)	15.7 ± 3.0^{a}	17.8 ± 3.4^{b}	37.2 ± 9.0^{a}	41.1 ± 5.5^{b}	A
Biceps CSA (mm^2)	297.8 ± 106.7^{a}	462.0 ± 216.3^{b}	807.2 ± 207.5^{a}	792.9 ± 256.7^{b}	A
Triceps CSA (mm^2)	$273.8 \pm 94.6^{a,c}$	$426.5 \pm 177.7^{b,c}$	$786.5 \pm 295.4^{a,d}$	$956.8 \pm 282.5^{b,d}$	A,T
Quads CSA (mm^2)	603.4 ± 170.8^{a}	712.7 ± 183.7^{b}	1331.3 ± 518.3^{a}	1436.1 ± 342.1^{b}	A
Hamstrings CSA (mm^2)	1195.2 ± 336.3^{a}	1346.0 ± 510.6^{b}	2231.5 ± 596.4^{a}	2287.7 ± 527.9^{b}	A
Body Fat percentage (%)	17.8 ± 6.3	20.1 ± 12.0	17.9 ± 4.8	14.8 ± 3.8	
Lean body mass (kg)	28.3 ± 4.8^{a}	31.9 ± 5.2^{b}	65.6 ± 8.1^{a}	63.5 ± 5.1^{b}	A

(Table 4.1 continued on next page)

Table 4.1: Physical characteristics of the endurance-trained and untrained boys and men – (continue from previous page)

	Children		Adults		
	Control (n=18)	Endurance (n=12)	Control (n=20)	Endurance (n=15)	**Effect**
Triceps skinfold thickness(mm)	10.9 ± 4.4	12.2 ± 7.2[a]	11.2 ± 3.7[b]	7.0 ± 2.2[a,b]	A, A*T
Biceps skinfold thickness(mm)	6.7 ± 2.9[a]	7.0 ± 4.2[b]	5.4 ± 1.9[a]	4.6 ± 1.3[b]	A
Anterior thigh skinfold thickness(mm)	18.1 ± 7.7	16.2 ± 6.9[a]	16.7 ± 6.0[b]	10.8 ± 3.9[a,b]	A,T
Posterior thigh skinfold thickness(mm)	14.6 ± 5.2	13.5 ± 5.8	17.5 ± 7.0[a]	10.0 ± 4.1[a]	T, A*T

Values are presented as M ± SD. Similar superscripts indicate pairwise significant differences ($p < 0.05$).
Similar letters display significant difference between groups.
A = Age effect, T = training effect, A*T = Age and training interaction ($p < 0.05$).

4.1 Peak torque

In absolute terms, men were significantly stronger than the boys (see Figure 4.1a). There was an age-by-training interaction, reflecting the fact that the endurance-trained boys were significantly stronger than the untrained boys, while no such difference was apparent in the adults. When peak torque was normalized to muscle CSA as measured via ultrasound (see Figure 4.1b), an age effect was still apparent, reflecting the fact that on average, normalized torque was higher in the men. There was also an age-by-training interaction ($p=0.053$), reflecting the fact that only the untrained men had higher normalized torque compared with trained men. The pattern was reversed in the boys, although the difference was not significant.

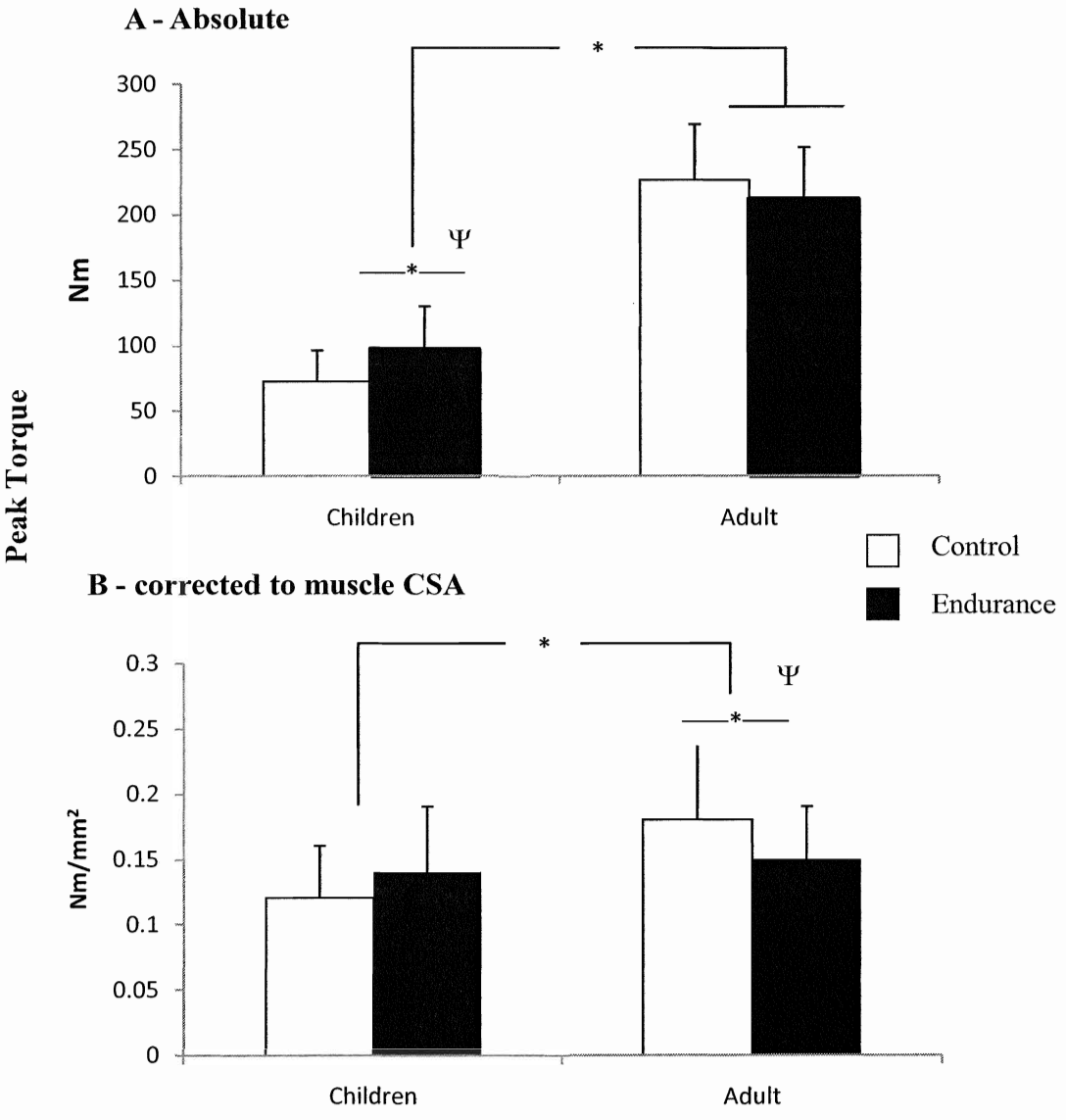

Figure 4.1: Knee extension peak torque of the endurance-trained and untrained boys and men M±SD. A. Peak torque in absolute values *p<0.05, Ψ=age*training interaction(P<0.05). B. Peak torque corrected to muscle CSA (Ultrasound), *p<0.05, Ψ=age*training interaction (p=0.053).

4.2 Rate of torque development

In absolute terms, men exhibited a more rapid RTD than boys during knee extension (see Figure 4.2a). No differences were observed between trained and untrained groups within each age group. This was also the case when RTD was normalized to peak

torque (see Figure 4.2b). No age-by-training interactions were apparent either in absolute terms or when RTD was normalized to peak torque.

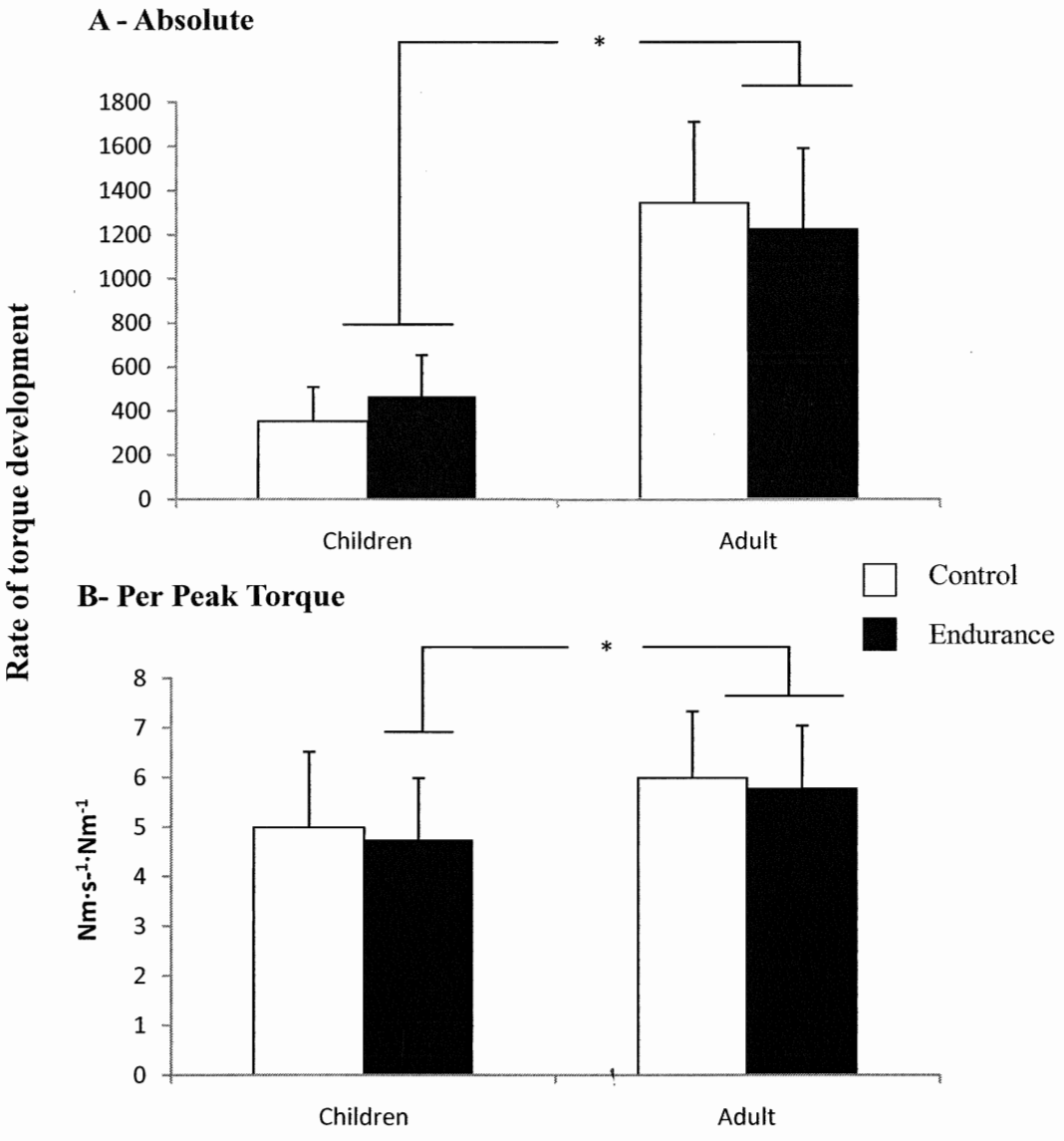

Figure 4.2: Knee extension RTD of the endurance-trained and untrained boys and men. M±SD. *$p<0.05$. A. RTD in absolute values, B. Rate of torque development corrected to peak torque.

4.3 Rate of Muscle activation (Q_{30})

The men had significantly higher absolute Q_{30} compared with the boys (See figure 4.3a). There was a training effect, reflecting the fact that on average, the endurance-trained athletes had higher rate of muscle activation compared with the non-athletic groups. More importantly, there was an age-by-training interaction, which reflects the fact that the endurance-trained men had significantly higher Q_{30} compared with their age-matched untrained group. The difference between the trained and untrained boys was not significant.

When Q_{30} was normalized to peak EMG amplitude (See figure 4.3b), age and training effects were still significant. There was also a trend toward age by training interaction ($p=0.065$), reflecting the fact that the endurance-trained men had significantly higher Q_{30} compared with their age-matched untrained group. No such difference was apparent in the boys. That is, the training effect was due predominantly to the difference between the trained and untrained adults (but not the children).

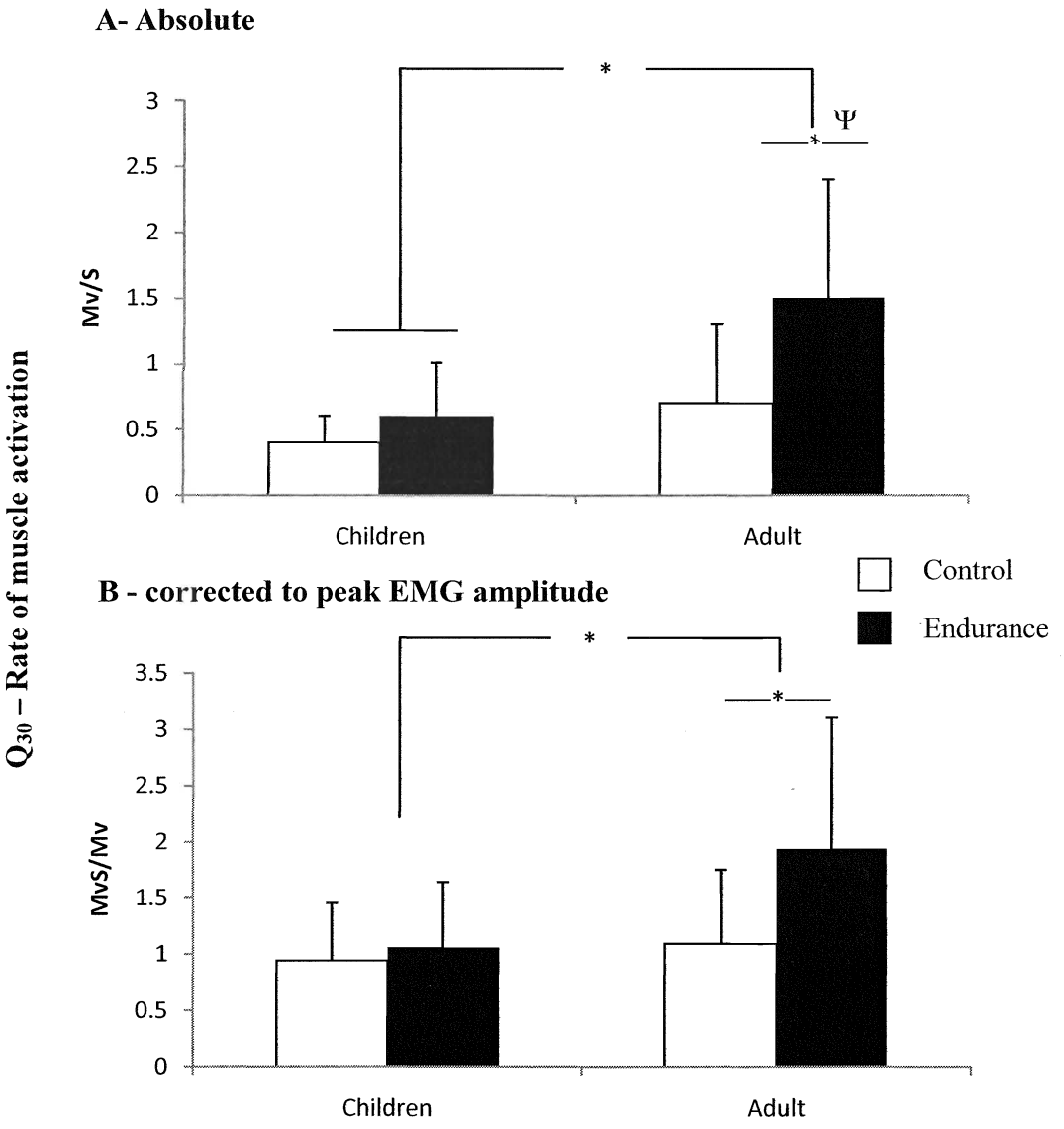

Figure 4.3: Knee extension rate of rise in EMG activity (Q_{30}) of the endurance-trained and untrained boys and men. M±SD. *p<0.05. Ψ=age*training interaction(P<0.05). A. Q_{30} in absolute values, B. Q_{30} corrected to peak EMG amplitude, *p<0.05 Ψ=age*training interaction (P=0.065).

4.4 Electromechanical delay (EMD)

There was no significant age or training effect in agonist EMD between age and training groups (see figure 4.4). However there was a trend toward longer EMD in the boys compared with the adult group (p=0.077).

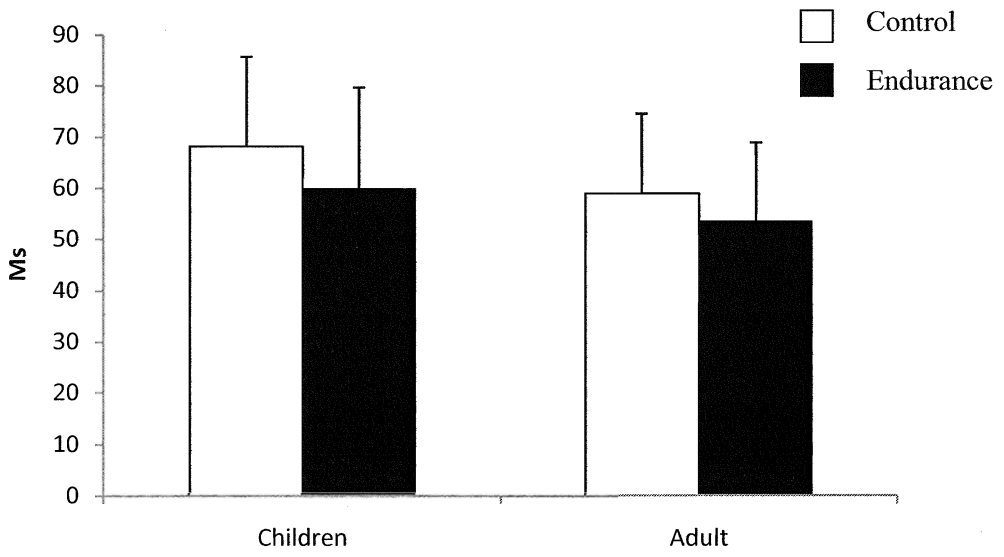

Figure 4.4: Knee extension Electromechanical Delay (EMD) of the endurance-trained and untrained boys and men. M±SD. Age effect (P=0.077)

4.5 Time to peak torque and peak RTD

There were no significant differences in time to peak torque between the two age and training groups (see figure 4.5a). However, the time to peak RTD was significantly longer in the boys compare with the men (See figure 4.5b). No training effect or training by age interaction were evident.

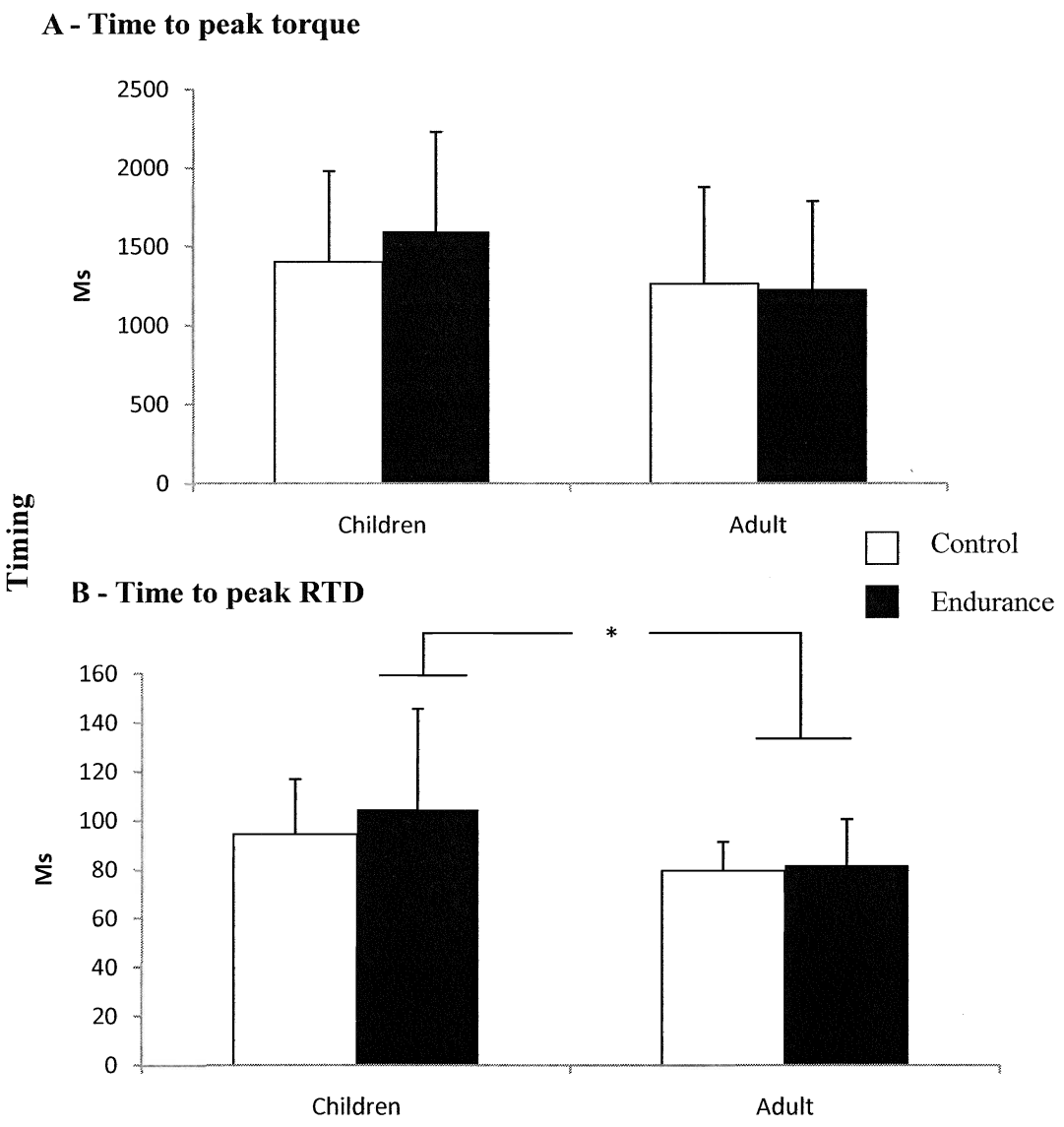

Figure 4.5: A. Knee extension time to peak torque of the endurance-trained and untrained boys and men. M±SD. Age effect (P=0.099). B. Knee extension time to peak RTD of the endurance-trained and untrained boys and men. M±SD. *P<0.05.

4.6 Co-activation

The co-activation index was not significantly different between the untrained boys and the untrained men groups (0.14 ± 0.1 vs. 0.13 ± 0.06) and between the endurance-trained boys and endurance-trained men groups (0.15 ± 0.17 vs. 0.09 ± 0.07). No age effect or age by training interactions were found.

4.7 Correlations

Correlations between knee extension torque and RTD variables on one hand, and EMG variables on the other hand were calculated in order to examine the relationship between those variables (Appendix Y). In the whole group, peak torque was positively correlated with peak EMG_{amp} ($r = 0.33$). However, when subjects were grouped according to their age, no correlation was apparent in either age group. Peak RTD was positively correlated with Q_{30}, whether RTD and Q_{30} were expressed in absolute or normalized values ($r = 0.41$ and $r = 0.36$ respectively). Yet, when subjects were separated by age group, normalized peak RTD was positively correlated with normalized Q_{30} ($r = 0.45$) only in the men. Normalized Q_{30} was negatively correlated with EMD, in the whole group ($r = -0.53$), as well as in the men ($r = -0.58$). However, no correlation was apparent in the boy's data.

4.8 Repeated measures analysis

Table 4.3 presents the results of the ANOVA for repeated measures analysis highlighting only the significant effects. Appendix AA presents the full ANOVA for repeated measures results. The repeated measures two-way ANOVA performed take into account all four contractions in each analysis. An age effect was apparent in all variables examined, which reflects the fact that the pattern of age differences was a persistent finding across all four types of contractions tested. On average, the men had higher torque, RTD and Q_{30} values than the boys, whether those variables were expressed in absolute or normalized terms. Furthermore, time to peak RTD and peak torque as well as EMD were significantly longer in the boys compared with the men. The co-activation index was lower in the men compared with the boys. In addition, the training effect was

apparent only in co-activation index, which reflects the fact that on average the endurance-trained athletes had lower co-activation index than the untrained control subjects.

An age-by-training interaction were apparent in few of the variables. There was an age-by-training interaction for absolute peak torque, reflecting the fact that the endurance-trained boys were significantly stronger than their age matched untrained subjects, this was not the case with men. There was an age-by-training interaction when Q_{30} was normalized to peak EMG amplitude. This interaction reflects the fact that the endurance-trained men had higher Q_{30} values than their age matched control subjects, while no difference was apparent between the boys groups.

Table 4.2: Repeated measures including all four types of contractions

		Age effect	Training effect	Age*training interaction
Torque:	Absolute	<0.001	-	0.018
	Per CSA_u	0.001		
RFD:	Absolute	<0.001	-	-
	Per torque	<0.001	-	-
Q_{30}:	Absolute	<0.001	-	-
	Per EMG_{amp}	<0.001	-	0.025
EMD		<0.001	-	-
T to peak torque		<0.001	-	-
T to peak RFD		<0.001	-	-
Co-activation		0.010	0.025	-

A = Age effect, T = Training effect, A*T = Age and training interaction ($p < 0.05$).

CHAPTER 5: DISCUSSION

The objective of this study was to compare maximal isometric torque and RTD, along with the pattern of muscle activation during elbow and knee flexion and extension in pre-pubertal muscle-endurance-trained and minimally-active boys and in muscle-endurance-trained and minimally-active men. Our main results showed that men were stronger, had higher RTD and Q_{30} than the boys, whether expressed in absolute values or normalized to mCSA, peak torque or peak EMG amplitude respectively. When torque was normalized to mCSA the untrained men had higher torque compared with the endurance-trained men. However, more interestingly, the endurance-trained men had significantly higher Q_{30} compared with their age-matched untrained group. The training effect in Q_{30} was due predominantly to the difference between the trained and untrained adults. EMD was consistently longer in the boys during all four types of contractions tested. No differences were found between the two boys groups in neither Q_{30} and EMD examined. Lastly, Q_{30} negatively correlated with EMD, and normalized peak RTD was positively correlated with normalized Q_{30}. These correlations were apparent in the group as a whole and in the men, but not in the boys.

5.1 Peak torque

As expected adults were significantly stronger than the boys (Figure 4.1a). This could be related to the higher mCSA in the adults, and is supported by a whole body of literature illustrating the effect of the muscular mass on MVC (MacIntosh et al. 2006). Thus, normalizing peak torque for mCSA area, greatly reduced peak torque age-differences (Figure 4.1b), but it remained lower in the boys compared with the men. Our results agree with previous studies, which also demonstrated a lower CSA-normalized

torque in children compared with adults in different muscle groups using anthropometry and ultrasound (Falk et al. 2009b; Halin et al. 2003; Seger & Thorstensson, 2000; Kanehisa et al. 1994; Grosset et al. 2008; Davies, 1985; Kanehisa et al. 1995).

These data suggest that other factors, such as possible differences in muscle activation, moment arm, muscle composition or co-activation may also explain age-related differences in upper and lower body strength. Moment arm and muscle composition were not assessed in the present study. Since all contractions were isometric, it is assumed that potential differences in moment arm did not play a main role. Similarly, it is assumed that muscle composition is similar in children and adults (Davies et al. 1983; Davies et al. 1985; Belanger & McComas, 1989). The results of the present study suggest that at least some of the age-related difference is explained by difference in rate of muscle activation (Q_{30}), and not by co-activation.

It seems that the endurance training had a different effect on maximal strength in the men compared with the boys. Although no difference was observed between the endurance-trained men and untrained men in peak torque when expressed in absolute terms, when peak torque was normalized to mCSA the untrained men were significantly stronger than the endurance-trained men. No such pattern was apparent in the boys groups. The similar absolute torque in the trained and untrained men is consisted with the findings of Sleivert et al. (1995). However, our results of lower normalized torque in the trained men are contradictory to previous studies that reported adult endurance-trained athletes to be either stronger than sedentary subjects during maximal isometric knee extension (Lattier et al. 2003) or similar between the two groups during isokinetic knee extension contraction (Kanehisa et al. 1997). The discrepancy between our results and the

available literature could be due to different methods used to normalize peak torque and calculated mCSA. Kanehisa et al. (1997) calculated mCSA using calibrated formula and took into account limb's length, while we estimated mCSA from the muscle depth images obtained via ultrasound using the following formula: (Muscle depth/2)^2*π. Furthermore, we normalized peak torque to mCSA while Lattier et al. (2003) normalized peak torque to body mass. Indeed, when torque was normalized to body mass, no training effect was seen in the present study. Furthermore, the type of muscle contractions tested as well as the background and training history of the athletes in our study could also have contributed to the differences in the findings. In our study, the majority of the athletes were swimmers while the data in the literature are mainly from long distances runners or cyclists. Given the nature of each sport, it is likely that different loads were imposed on the muscle grouped assessed (Maffulli et al. 1994). It was suggested that swimmers are obliged by the medium in which they train to undergo a kind of continuous isokinetic muscle contraction (Astrand & Rodahl, 1986), which might affect the training adaptation. Furthermore it was suggested that endurance training, might comprise strength gains since it may bring a change in the MU recruitment pattern, with less fast-twitch fibres recruited after training (Lucia et al. 2000; Gaesser & Poole, 1996), as well as a decrease in the percentage of fast-twitch fibre cross-sectional area in the aerobic trained muscles (Thayer et al. 2000). This suggestion supports our findings of lower normalized peak torque in the trained men.

When torque was expressed in absolute terms, the endurance-trained boys were significantly stronger than their age-matched counterparts. However, no such difference was apparent with torque normalized to mCSA, which suggests that mCSA can explain

the difference between the two groups in our study. To the best of our knowledge, this is the first study to examine maximal strength in endurance-trained pre-pubertal boys. Therefore, no comparable data exist in the literature. However, it is well established in the adult literature that endurance training has a minimal effect on maximal strength (Sleivert et al. 1995; Kanehisa et al. 1997; Hickson, 1980; McCarthy et al. 2002; Grandys et al. 2008). It should be noted that two studies compared maximal isometric voluntary contraction of the knee extensors and elbow flexors between young athletes who participated in different types of sports such as: swimming, football, tennis and gymnastic. The gymnasts were stronger than all other athletes, when strength was corrected for body mass. However, no comparison with untrained boys was made in either study (Maffulli et al. 1994; Bencke et al. 2002).

The different training effect in the men compared with the pre-pubertal boys could be related to the use of different training modes (triathlon and swimming in the men vs. only swimming in the boys) and differences in intensities of applied training programs. It is possible that the absence of difference in peak torque between the boys groups in this study is a consequence of relatively moderate intensities used during the pre-pubertal boys swimming programs.

5.2 Rate of torque development (RTD)

The lower absolute RTD observed in the boys (Figure 4.2a) is partly explained by the dependency of RTD on peak torque, since the RTD calculation is based on the torque achieved during the contraction. Thus, normalizing RTD to peak torque can be useful in searching for other factors that might determine RTD (Holtermann et al. 2007). Only two studies have normalized children's RTD to peak torque, reporting lower values for elbow

flexion in pre-pubertal boys compared with men (Falk et al. 2009b; Asai & Aoki, 1996), as well as in elbow extension (Falk et al. 2009b). Our results correspond to Falk et al. (2009b) and Asai & Aoki (1996) and complement them with knee extension data. Therefore, children's lower RTD is a persistent finding, independent of their lower maximal strength and muscle group tested. These results suggest that factors other than muscle size such as muscle activation, elasticity of the muscle-tendon unit may also be involved in determining RTD, as is the case for peak torque.

No differences were found between the training groups, in either age group tested. Although limited data exist in the adult literature regarding differences between untrained controls and endurance athletes, our results are not surprising since the athletes in the current study were endurance-trained athletes involved mainly in sub-maximal steady muscle actions, rather than exerting explosive muscle actions. RTD has been shown to increase following heavy resistance training (Aagaard et al. 2002), and to be higher in athletes who mainly involved themselves in explosive type of training (Sleivert et al. 1995). However, following endurance training Sleivert et al. (1995) reported no difference in RTD in knee extensor between endurance-trained and sedentary controls, which support our findings.

Several indirect or field-based tests exist to measure explosive strength. Such methods include: vertical and countermovement jumps, force-velocity tests and different cycling tests (Izquierdo et al. 2002; Armstrong et al. 2008). Using those different methods, few studies compared explosive performance of endurance-trained athletes and untrained controls. Those studies found no difference in jumps performance between the two groups (Lattier et al. 2003), as well as no differences in force-velocity relationship

(Izquierdo et al. 2002). However, it is hard to relate those results to our current findings since pervious investigations which have compared performance in the countermovement vertical jump to strength and power in single-joint isometric tests, such as used in our study, found no correlation and relationship between the two measures (Ugarkovic et al. 2002; Anderson et al. 1991).

Thus, while our adult data are in agreement with the literature, our study is the first to report no differences in RTD between endurance-trained pre-pubertal boys and age-matched untrained counterparts.

5.3 Rate of muscle activation (Q_{30})

Rate of muscle activation (Q_{30}) is defined as the area under the EMG curve of the linear envelope of the detected EMG signal during the first 30 ms (Gottlieb et al. 1989), and it has been previously used to measure rate of increase in neural activation during a maximal task (Falk et al. 2009a,b; Gottlieb et al. 1989; Gabriel & Boucher, 2000). Our results confirmed previous findings (Falk et al. 2009b), that boys have lower Q_{30} compared with men. Additionally, endurance-trained men were able to activate their muscles much faster than untrained men, while no such training effect was apparent in the boys (Figure 4.3a and b). The pattern for increased Q_{30} in our adult athletes was a consistent finding throughout all four contractions tested, as illustrated by the results of the ANOVA for repeated measures analysis (Table 4.2). These results complement Lattier et al.'s (2003) findings who using the interpolated twitch technique reported that endurance-trained men had higher maximal voluntary activation of knee extensors compared with untrained counterparts. Furthermore, it seems that our results support De Luca et al. (1982) who suggested that untrained adults cannot activate all their MUs

and/or cannot activate them at an optimal firing rate during MVC. The increased muscle activation in endurance athletes is further supported by Lucia et al. (2000), who used a longitudinal study design to examine the changes in neuromuscular variables in respond to endurance training during a full cycling season. Their main finding was that in elite cyclists endurance training enhanced recruitment of type I MUs in active muscles, as suggested by rms-EMG data. They suggested that the additional MUs were composed mainly of type I, since lactate levels decreased while VO_2 values remained unchanged throughout the season. This was further supported by the decrease in mean power frequency during the competition period, which the authors attributed to a further improved ability to recruit additional slow MUs. Since in the current study, surface EMG electrodes were used to measure muscle activation, we were unable to differentiate between MUs recruitment and MUs firing rate. However, the higher and enhanced Q_{30} in our endurance athletes gives another support to the existing evidence in the literature that endurance training, may counteract the ability of the neuromuscular system to exert explosive actions (Maffiuletti et al. 2001), yet still enhance MUs recruitment and muscle activation in the trained muscles.

Increased neural activation involves adaptations at the motoreuron level, i.e., changes in motoneuron recruitment and/or firing frequency, alterations in synchronization of MU firing and possibly, higher incidences of discharge doublets (Gruber & Gollhofer, 2004). Beaumont & Gardiner (2003) reported that endurance training in rats changed the biophysical properties of motor neurons. Specifically, it resulted in a more hyperpolarized resting membrane potential, increased threshold for spike initiations and faster rise times for antidromic spikes. The authors argue that these

adaptations can modify the recruitment thresholds and discharge patterns of neurons. Although not tested in the current study, it is possible that these adaptations also occurred in the trained men supporting the finding of a higher Q_{30} in the endurance-trained athletes.

As was mentioned before, no difference in RTD was observed between the endurance-trained athletes and untrained subjects. However, significant differences between the two groups were observed in Q_{30}. Although the importance of neural influence and muscle activation on RTD has been suggested before (Hakkinen & Komi, 1986; Corcos et al. 1989). Hakkinen & Komi (1986) were unable to demonstrate a significant change in EMG/time curve to parallel improvement in RTD with resistance training. In our study a weak positive correlation ($r = 0.36$) was observed between normalized RTD and normalized Q_{30}. In the men, the correlation was ($r = 0.48$). This weak correlation and the unparallel difference in RTD and Q_{30} between the endurance-trained and untrained men might suggest that factors other than the rate of muscle activation are involved in determining the RTD.

A theoretical explanation for the higher Q_{30} in the men compared with the boys, may be that men had higher predominance of type II fibres in the knee extensors in particular, compared with the children (Halin et al. 2003). However, this hypothesis seems unlikely since the literature suggests that muscle fibre composition does not differ much from childhood to adulthood (Blimkie, 1989). Furthermore, since we tested endurance-trained athletes, this hypothesis seems even less likely since it has been previously reported that endurance-trained athletes have predominantly type I muscle fibres, and endurance training has even been suggested to alter muscle fibre

characteristics, promote transformation of type II muscle fibres to type I (Howald et al. 1985; Thayer et al. 2000; Short et al. 2005), as well as increase recruitment of mainly type I MUs (Lucia et al. 2000; Gaesser & Poole, 1996).

Alternatively, it has been suggested that pre-pubertal boys are less able to activate their neuromuscular system compared with adolescents and adults (Paasuke et al. 2000; Belanger & McComas, 1989). Furthermore, Ramsay et al. (1990) hypothesized that there may be a difference in neurological input to the prime movers during contraction, which could result in an increased recruitment of available MUs in men compared to boys. These suggestions could support our findings of lower Q_{30} in the boys.

To the best of our knowledge, this is the first study to examine any muscle activation index in endurance-trained pre-pubertal boys. It was suggested by Halin et al. (2002), that the neuromuscular system of children could be more sensitive to a training stimulus. Increased muscle activation following resistance training (Ramsay et al. 1990; Ozmun et al. 1994) and following gymnastic training (Halin et al. 2002) in pre-pubescent boys was reported before. Thus it seems that with the appropriate training stimulus pre-pubescent boys are able to increase their MU activation compared with untrained age-matched controls. However, we could not support this proposal in our study, since no training effect was apparent in our endurance-trained boys. The lack of training effect in the boys could possibly be attributed to the endurance training program characteristics which are substantially different from gymnastic and resistance training. Halin et al. (2002) suggested that in order to enhance MUs activation in pre-pubertal boys the training stimulus should be high such as in gymnastic. Gymnastic training involves a variety of eccentric and concentric loads as well as short bursts of highly explosive

activity, while the pre-pubescent swimmers in the current study were mainly involved in low intensity repetitive exercise.

Nevertheless, in view of our cross-sectional design, it is impossible to exclude genetic factors in our subjects, independent of their training status. Furthermore, given the differences in training volume and history of our boys and men athletes, it is possible that the relative training effect was different between children and adults in the current study.

5.4 Electro-mechanical delay (EMD)

EMD reflects muscle-tendon stiffness, excitation-contraction coupling, and muscle fibre conduction velocity (Halin et al. 2003; Cavagna & Komi, 1979). In the present study, no significant differences in EMD were found during knee extension between men and boys, regardless of training background (Figure 4.4). However, there was a trend towards a longer EMD in the boys ($p=0.077$). The number of subjects in our study could in part explain why we only observed a trend but not a significant difference.

However, when the EMD data from all four types of contractions was used in an ANOVA for repeated measured analysis, a significant age effect was apparent, which reflects the fact that EMD was consistently longer in boys compared with men. An age-related decrease in EMD has been reported earlier during maximal elbow flexion (Falk et al. 2009b; Asai & Aoki, 1996), maximal elbow extension (Falk et al. 2009b) as well as plantar-flexion twitch contraction (Grosset et al. 2005). The age difference in EMD was attributed to lower musculo-tendinous stiffness in pre-pubertal boys compared with adults (Lambertz et al. 2003) and to lower muscle activation or muscle fibre conduction velocity in boys (Halin et al. 2003). Furthermore, Falk et al. (2009b) proposed that the boys'

longer EMD is partly explained by their lesser recruitment or utilization of the faster, higher-threshold MUs. This hypothesis was supported by Asai & Aoki (1996) and Halin et al. (2003), who both argued that children involve fewer type-II fibres during MVCs than do adults. The longer EMD in our study was further accompanied with significantly longer time to maximal RTD in the boys (Figure 4.5b) and lower Q_{30}. Thus, our findings further support the proposal that boys exhibit lower levels of muscle activation compared with men and may be less able to recruit their higher hierarchy type II MUs.

We were unable to demonstrate a training effect in EMD in either age group, even when the ANOVA repeated measures analysis was used. This again could be explained by the lower number of participants in our study and could possibly attribute to the fact that the knee extensors might be at a higher level of conditioning at the beginning of the study than the upper body muscles even in our untrained subjects. The quadriceps, by its weight-bearing role during habitual activity, is particularly important in daily activities; therefore, it may be at a higher initial level of conditioning than the upper body muscles, which are used less frequently on a habitual basis, even in our control subjects.

Our results are contradictory to Grosset et al. (2009), who found EMD to be significantly shorter after 10 weeks of endurance training in men. In humans, tendon stiffness was reported to increase after endurance training (Buchanan & Marsh, 2001), and the muscle-tendon complex was found to be less compliant in long distance runners than in untrained individuals (Kubo et al. 2000). Although it was suggested that EMD is highly depended on the muscle-tendon stiffness (Cavagna & Komi, 1979), Grosset et al. (2009) found that musculo-tendinous stiffness changes could account only for the 20% of the variance in the EMD changes. This suggests that factors other than the elasticity of

the muscle-tendon unit can affect the EMD, as was mentioned earlier. There was a significant negative correlation between EMD and normalized Q_{30} ($r = -0.58$) in the men, suggesting that the shorter the EMD the higher the Q_{30}. Furthermore, as stated earlier, the endurance-trained men had significantly higher Q_{30} than the untrained men. This correlation suggests a link between the rate of muscle activation and EMD. Nevertheless, we were unable to demonstrate significant differences in EMD between the endurance-trained and the untrained groups.

5.5 Co-activation

Another factor that can affect muscle strength generation is co-activation of the antagonist muscle groups. In situations of increased antagonist muscle activation beyond the level necessary for joint stability, peak force production might be compromised (Stackhouse et al. 2005). In the current study, age differences in co-activation index could not be discerned during knee extension. Thus, during isometric contraction like the one performed in our study, co-activation does not appear to be a substantial contributor to the child-adult differences observed in measured torque or RTD. These findings are in line with previous studies which reported no observed differences in co-activation between children and adults during isometric contraction (Falk et al. 2009b; Morse et al. 2008; Falk et al. 2009a). It should be noted that using the ANOVA for repeated measures analysis, an age effect was observed, which is in line with some reports in the literature (Lambertz et al. 2003). Nevertheless, in all groups, co-activation was very low (3-10%), implying that the effect of co-activation on produced torque was minimal. Furthermore, no differences in co-activation were observed between the training groups in either age group. These findings are in line with Osternig et al. (1986) and Westing et al. (1991),

who found co-activation levels of adult long distance runners to be almost the same as that of untrained individuals.

5.6 Limitations

There are several limitations inherent in the present study. Due to the cross-sectional design of the current study, it is impossible to exclude the influence of genetic factors in our subjects disregarding their training status. Originally, only endurance-trained swimmers men and boys who were not involved in any sort of resistance training were desired for comparison. However, in view of the difficulties in subject recruitment, it was decided to also include adult triathletes, as well as swimmers who might participate in low intensity resistance training. In spite of our recruitment efforts, the endurance-trained groups were still relatively small (n = 12 and 15 for boys and men, respectively). The low number of subjects may have been insufficient to demonstrate potential interaction between age and training in some variables (e.g. EMD, co-activation, Q_{30}). However, we were able to demonstrate a consistent age difference in all variables tested.

Another possible limitation is the fact that we did not use evoked twitches and the interpolated twitch technique in order to measure maximal muscle activity. This was done to limit pain or discomfort, especially in the children.

Although surface EMG is widely used in assessment of muscle activation in both children and adults, it has several limitations when assessing muscle activity. The EMG signal recorded from the skin surface is a composite of both the underlying physiological processes that generate myoelectric energy and the multitude of factors that affect the characteristic of the recording (Kamen & Caldwell, 1996). The EMG pattern of muscles

is dependent on recording conditions like recording site, electrode type, filter setting and sampling frequency (Finsterer, 2001). The EMG methodology used in this study did not include determination of the motor point in muscle groups prior to electrode placement. Although placement was kept as constant as possible between subjects, the location of the motor point in a given muscle varies between subjects. Therefore, electrode placement relative to the motor point may have been imprecise in the present study. It is possible that the location of the electrode with respect to the motor points in the muscle has influenced the amplitude of the detected signal, as was previously suggested by (De Luca, 1997). Therefore, in order to minimize this effect, we normalized our Q_{30} data for each subject to their respective peak EMG amplitude. Thus, the analysis focused on timing and rate of change, rather than on amplitude.

CHAPTER 6: CONCLUSION

6.1 General Conclusions

During maximal voluntary isometric knee extension men were stronger, had higher RTD and higher rate of muscle activation, whether absolute or normalized values were examined. Moreover, the boys exhibited longer EMD and time to peak RTD. In addition, endurance-trained men had lower peak torque compared with untrained men, yet they also exhibited significantly higher Q_{30}. No training effect was apparent in the boys. Consequently, the current findings of boys' consistently lower peak torque and RTD, regardless of training status, further supports the notion of lower muscle activation in children during maximal force generation. The higher Q_{30} of the endurance-trained men might reflect neural adaptations to training, regardless of the intensity of the training stimulus. The lower peak torque may suggest a higher involvement of type I muscle fibres in the endurance-trained athletes, as was previously suggested in the literature (Lucia et al. 2000; Gaesser & Poole, 1996).

6.2 Significance and future directions

Endurance training has been known to improve cardiovascular fitness and reduce the risk of certain diseases, such as heart disease and obesity in adults, as well as in children (Janz et al. 2002; Sallis & Patrick, 1994). Furthermore, there are well-founded recommendations for youth physical activity that will improve cardiovascular or bone health. However, corresponding recommendations for neuromuscular functional enhancement in youth are lacking. While some recommendations for neuromuscular training exist for adults (Gabriel et al. 2006), little is known about neural activation and adaptations to training during childhood, specifically endurance training.

This study was designed in order to help gather basic physiological data and shed some light on muscle strength, along with associated neuromuscular mechanisms in boys, trained and untrained. Enhanced muscle performance, and more specifically, enhanced neuromuscular function among athletes highlights the importance of physical activity and training. This data set provides initial characterization of neuromuscular function that will allow for future practical understanding and recommendations regarding the design and type of activities that will more effectively affect strength and neuromuscular function in youth. More so, physiological adaptations to endurance training in the healthy child, such as but not limited to those observed in the present study, may eventually provide a basis for exercise training in rehabilitation programs for children with different diseases and disorders.

The current study was the first to investigate the effect of endurance training on muscle strength and pattern of muscle activation in boys. However, since we used a cross-sectional design with its inherent limitations, future research should try to use a longitudinal design to better understand the effect of growth, development and activity levels (e.g., endurance training) on peak torque and muscle activation patterns during dynamic and sub-maximal isometric contractions. Furthermore, the possible effects of endurance training on various muscle groups during different developmental stages should be investigated using training intervention studies.

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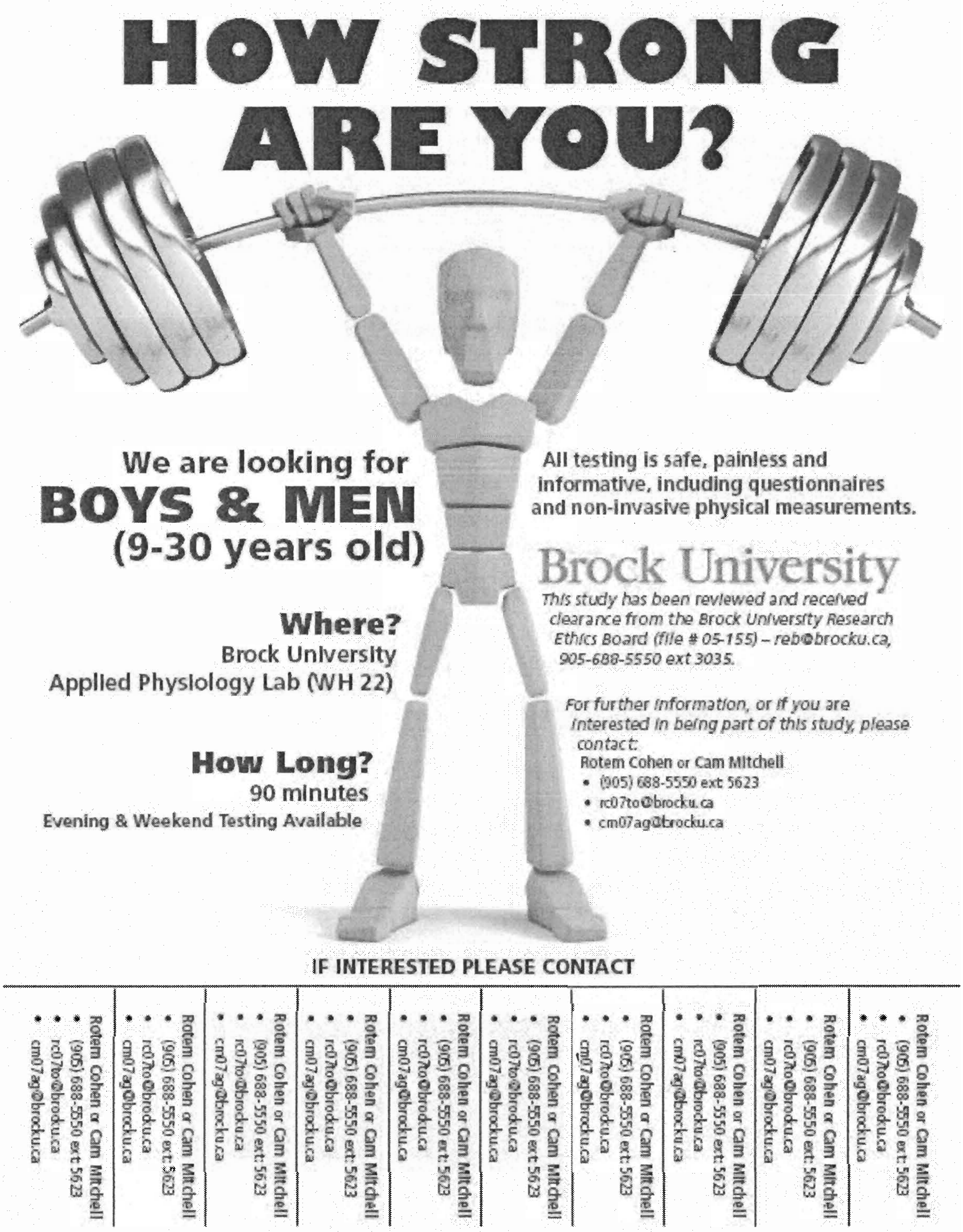
Appendix A: Recruitment poster



Appendix B: Invitation letter

Invitation Letter

MUSCLE ACTIVATION IN CHILDREN VERSUS ADULTS

Principal Investigator: Dr. Bareket Falk, Department of Physical Education and Kinesiology, Brock University

We would like to invite you to participate in the present study, which investigates muscle strength and the way muscle work in children vs. adults.

The **purpose** of this research project is to compare muscle function in children of different age groups and adults – athletes and non-athletes. In other words, we would like to know if growth and participation in certain sports affect the way muscles function.

Tests and measurements will require two visits of about **1 hr**. Briefly, measurements include muscle function (arms and legs), measurement of muscle size (using ultrasound) and filling out several questionnaires. All measurements are safe and painless.

Participation in this project will allow you to have personal information on your muscle strength, as well as other information, such as height, weight and percent body fat.

This research is being performed only by Brock University researchers in the Applied Physiology Laboratory.

If you have any pertinent questions about your rights as a research participant, please contact the Brock University Research Ethics Officer (905 688-5550 ext 3035, reb@brocku.ca)

If you have any questions, please feel free to contact us.

Thank you

Principal Investigator:

Bareket Falk

Department of Physical Education and Kinesiology
Faculty of Applied Health Science
Brock University
Tel: 905-688-5550 ext:4979/5623
Study coordinators: Rotem Cohen and Cam Mitchell

E-mail: rc07to@brocku.ca

This study has been reviewed and received ethics clearance through Brock University's Research Ethics Board (file # **05-155**]

Appendix C: Informed consent

INFORMATION & CONSENT TO PARTICIPATE IN RESEARCH

MUSCLE ACTIVATION IN CHILDREN VERSUS ADULTS

You are being invited to participate in a research study being conducted by the investigators listed below. Prior to participating in this study please read this form to find out about the purpose and the tests of this study. For the tests you will have to visit the Exercise Physiology Laboratory (WH17, Brock University). This study is sponsored by the Faculty of Applied Health Sciences of Brock University.

INVESTIGATOR:	DEPARTMENT:	CONTACT:
Dr. Bareket Falk	FAHS*, Brock U	(905) 688-5550 x4979
Dr. Nota Klentrou	FAHS, Brock U	(905) 688-5550 x4538
Dr. David Gabriel	FAHS, Brock U	(905)688-5550 x4362

Students working under the supervision of Drs. Falk, Klentrou or Gabriel.

* FAHS = Faculty of Applied Health Sciences

PURPOSE:

The objective of this study is to examine whether children of different age groups and adults differ with respect to how muscle timing and activation change while performing a maximal and submaximal effort task.

DESCRIPTION OF TESTING PROCEDURES:

If you agree to volunteer for this study you will partake in two testing sessions (approximately 90 min). At the end of the study, you will be given a summary of the findings, upon request.

You will undergo the following measurements or procedures:

1. Completing questionnaires, outlining your medical history, physical activities and pubertal status. The questionnaire used to measure pubertal status involves looking at pictures of male and female genitalia and deciding which stage of

puberty you best match. This will be carried out in a private room to avoid any uneasiness. In all questionnaires, you may choose not to answer any question without penalty.

2. Determination of your body composition (percent body fat), using measurements of height, weight and skinfold thickness. Biceps circumference measures will also be taken. This procedure is quick and causes no discomfort.
3. Muscle force will be evaluated in the upper and lower extremities (arms and legs). This involves 10-15 trials of exerting maximal (all out) elbow and knee flexion and extension force (bending and straightening the arm and the leg) and three trials of submaximal (40% of maximal) elbow and knee flexion and extension force. Participants will first do a few warm-up trials. This procedure may result in muscle soreness within 48 hours of the test. If these effects do occur, it will only be temporary.
4. Recording voluntary muscle activity using Electromyography. This measures the electrical signal of muscle from the skin surface. This procedure involves the application of surface electrodes for the biceps and triceps of the arm, and hamstring muscles in the thigh. Before electrode placement with electrolyte gel, the skin surface will be shaved, lightly abraded, and cleansed with alcohol. There is a possibility of slight skin irritation. Washing the gel from the skin surface and applying lotion following the test will minimize irritation.
5. Reflexes: Tendon reflexes will be examined at the knee and at the ankle. This is performed by tapping the tendon below the knee and at the back of the ankle using a small rubber-tipped "hammer" The "hammer" is very similar to the one used by physicians to test reflexes, expect that the force applied and the timing can be measured. The procedure does not involve any pain or discomfort.
6. Muscle size: Muscle thickness will be measured using ultrasound. This ultrasound device consists of a main unit and a hand-held probe. A think layer of gel is applied to the following muscles: biceps brachii, triceps, rectus femoris, and biceps femoris. The measurement is made by passing the probe back and forth over the muscle.There is no discomfort associated with this measurement. Measurement requires approximately 15-20 min.

It is recommended that you come for the measurements in shorts and a t-shirt.

CONFIDENTIALITY:

All your data collected during this study will remain confidential and will be stored in offices and on secured computers to which only the principal and co-investigators have access. You should be aware that the results of this study will be made available to scientists, through publication in a scientific journal but your name and any personal data of you will not appear in compiling or publishing these results. Data will be kept for 5 years after the date of publication, at which time all information will be destroyed. Additionally, you will have access to your own data, as well as the group data when it becomes available and if you are interested.

PARTICIPATION & WITHDRAWAL

You can choose whether to participate in this study or not. You may remove your data from the study if you wish. You may also refuse to answer any questions posed to you during the study and still remain as a subject in the study. The investigators reserve the right to withdraw you from the study if they believe that it is necessary.

RISKS AND BENEFITS

The only foreseeable risks involved in participation include:

a) Possible muscle soreness within 48 h of the test. If this occurs, it will only be temporary.
b) Possible skin irritation from cleaning the skin with alcohol and applying surface electrodes. This can be minimized by washing the skin and applying skin lotion.
c) Some questionnaires may pose a potential embarrassment. In such a case, you need not reply to any question you do not wish to.

Participation will allow you to become exposed to a research protocol, contribute to the advancement of science, and gain knowledge about the function of one's own body. Additionally, if an unusually low or high result is attained for any of the measurements, reflecting a possible health-related problem, you will be alerted and advised to consult your physician. All results will be provided to you upon request.

RIGHTS OF RESEARCH PARTICIPANTS

You will receive a signed copy of this ethics form. You may withdraw your consent to participate in this study at any time, and you may also discontinue participation at any time without penalty. In signing this consent form or in participating in this study you are not waiving any legal claims or remedies. This study has been reviewed and received clearance from the Brock University Research Ethics Board (file #05-155. If you have any pertinent questions about your rights as a research participant, please contact the Brock University Research Ethics Officer (905 688-5550 ext 3035, reb@brocku.ca)

INFORMATION:

Please contact Dr. Bareket Falk at 905-688-5550(X4979), Dr. Nota Klentrou at 905-688-5550(X4538), Dr. David Gabriel at 905-688-5550(X4362), if you have any questions about the study.

I HAVE READ AND UNDERSTAND THE ABOVE EXPLANATION OF THE PURPOSE AND PROCEDURES OF THE PROJECT. I HAVE ALSO RECEIVED A SIGNED COPY OF THE INFORMATION AND CONSENT FORM. MY QUESTIONS HAVE BEEN ANSWERED TO MY SATISFACTION AND I AGREE TO PARTICIPATE IN THIS STUDY.

SIGNATURE of PARTICIPANT DATE

WITNESS DATE

PRINTED NAME OF WITNESS

INVESTIGATOR

In my judgment the participant is voluntarily and knowingly giving informed consent and possesses the legal capacity to give informed consent and participate in this research study.

SIGNATURE OF INVESTIGATOR DATE

Appendix D: Medical/Screening Questionnaire

SUBJECT SCREENING AND MEDICAL HISTORY QUESTIONNAIRE

Muscle Activation in Children versus Adults

APPLIED PHYSIOLOGY LABORATORY

DEPARTMENT OF PHYSICAL EDUCATION AND KINESIOLOGY

BROCK UNIVERSITY

Name: _____ Date: _____ ID: _____

Date of Birth: _____

Dominant Hand: What hand do you write with? _____

Dominant Leg: What foot do you kick with? _____

Your responses to this questionnaire are confidential. If you answer "YES" to any of the following questions, please give additional details in the space provided and discuss the matter with one of the investigators. You may refuse to answer any of the following questions.

1. Have you ever had any major joint instability or ongoing chronic pain such as in the knee, back or elbow?

   YES NO

2. Are you currently taking any medication (including aspirin) or have you taken any medication in the last two days?

   YES NO

3. Have you taken any medication in the past six months?

   YES NO

4. Is there any medical condition with which you have been diagnosed and are under the care of a physician (e.g. asthma, diabetes, anorexia)?

   YES NO

5. Do you, or have you in the past, engaged in physical activity on a regular basis?

YES NO

6. If YES, what sport activities do you engage in and how many hours per week do you participate in these activities? (use other side of paper).

Appendix E: Subject Checklist – Biodex (for All Subjects)

Subject Checklist

Date:_____ Subject ID:_____

Gender: M / F Subject name:_____

Dominant arm: R / L Dominant leg: R / L

Date of birth:_____ Age:_____

Machine Settings (inches)

Chair Height:_____ Dynamometer Tilt:_____

Chair Front/Back:_____ Attachment Length:_____

Chair Rotation:_____ Seat Back:_____

Dynamometer Left/Right:____ Lap Strap in Place:_____

Dynamometer Height:_____ Limb Weight:_____

Warm-Up Order:

Elbow: FLEX, EXT / EXT, FLEX

Knee: FLEX, EXT/ EXT, FLEX

Test Order I ____

Elbow: FLEX, EXT / EXT, FLEX
FLEX

Knee: FLEX, EXT / EXT, FLEX
FLEX

Test Order II ____

Knee: FLEX, EXT / EXT,

Elbow: FLEX, EXT / EXT,

Check off:

Elbow: Chest straps in place ☐ Lap strap in place ☐

Knee: Chest straps in place ☐ Lap strap in place ☐ Thigh strap in place ☐

Elbow Flexion/Extension

Arm position: 90 degrees ☐

MVC Flexion Repetitions

*Scaling:*_____

Trial #	**Peak Torque**	**Time of Peak**
1		
2		
3		
4		
5		
Rest	Y/N	
6		
7		
8		
9		
10		

Feedback following the Set:

_____

_____

_____

_____

_____

MVC Extension Repetitions

*Scaling:*_____

Trial	**Peak Torque**	**Time of Peak**
1		
2		
3		
4		
5		
Rest	Y/N	
6		
7		
8		
9		
10		

Feedback following the Set:

_____

_____

_____

_____

_____

Knee Flexion/Extension

Thigh position: 120 degrees ☐

Knee Position: 90 degrees ☐

MVC Flexion Repetitions

*Scaling:*_____

Trial #	**Peak Torque**	**Time of Peak**
1		
2		
3		
4		
5		
Rest	Y/N	
6		
7		
8		
9		
10		

Feedback following the Set:

_____

_____

_____

_____

MVC Extension Repetitions

*Scaling:*_____

Trial	**Peak Torque**	**Time of Peak**
1		
2		
3		
4		
5		
Rest	Y/N	
6		
7		
8		
9		
10		

Feedback following the Set:

_____

_____

_____

_____

Appendix F: Anthropometric measurements form

ANTHROPOMETRIC MEASUREMENTS

NAME: _____ TEST DATE (M/D/Y): _____

ID NUMBER: _____

GENDER: M / F DOMINANT ARM: R / L

DATE OF BIRTH (M/D/Y): _____ AGE: _____

SUBJECT HEIGHT (cm): _____ SEATED HEIGHT (cm): _____

(Table = 75.5 cm)

SUBJECT WEIGHT (kg): _____ FOREARM LENGTH (cm): _____

UPPER ARM CIRCUMFERENCE (cm): _____

TRIAL 1	TRIAL 2	TRIAL 3	MEDIAN

THIGH CIRCUMFERENCE (cm): _____

TRIAL 1	TRIAL 2	TRIAL 3	MEDIAN

MUSCLE DIAMETER (mm)

MUSCLE TESTED	TRIAL 1	TRIAL 2	TRIAL 3	MEDIAN
BICEPS BRACHII				
TRICEPS BRACHII				
BICEPS FEMORIS				
VASTUS LATERALIS/MEDIALIS/ RECTUS FEMORIS				

SKINFOLD MEASUREMENT:

SITE	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 4 (>1 mm diff)	MEDIAN
TRICEP					
BICEP					
SUBSCAP.					
SUPRAILIAC					

SUM OF SKINFOLDS (mm):

SUM @2 S.F _____

(2 Skinfold sites = Subscap+Tricep)

SUM @4 S.F _____

% BODYFAT _____

SKINFOLD MEASUREMENT OF THE THIGH

SITE	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 4 (>1 mm diff)	MEDIAN
ANTERIOR					
POSTERIOR					
MEDIAL					
LATERAL					

SUM OF SKINFOLDS (mm):

SUM @4 S.F _____

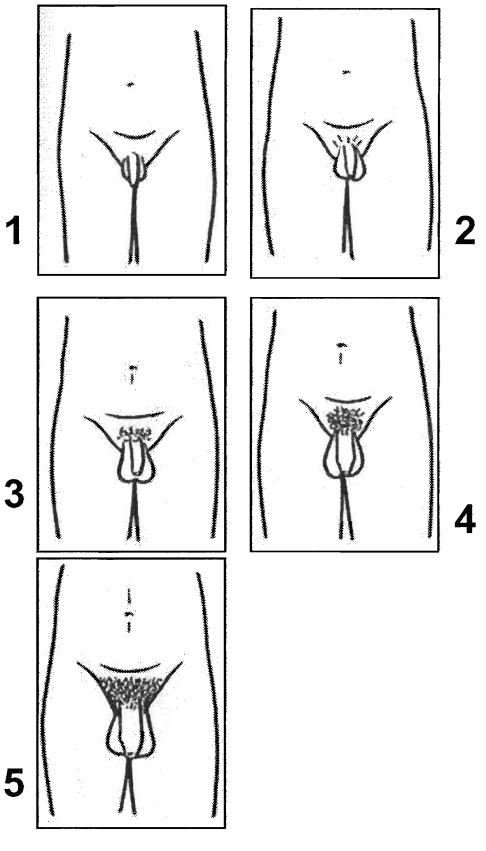
Appendix G: Pubertal Stage Questionnaire (Tanner, 1962)

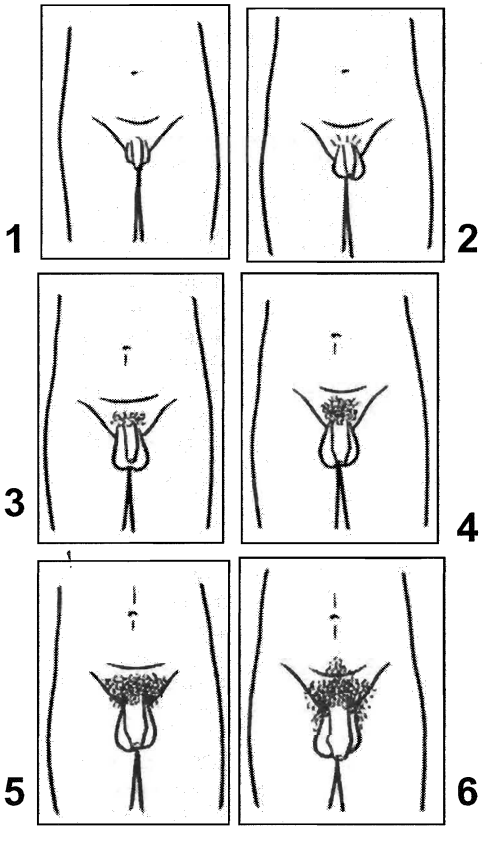
Name: _____ Date: _____ I.D: _____

Pubertal Stage

This survey will be used to assess the maturational levels of the participant. For each photo choose the appropriate stage and place an X in the corresponding square.

• Please circle the box that looks most like you		• Please look at the pubic hair only • Please circle the box that looks most like you





Appendix H: Godin-Shephard Leisure-Time Exercise Questionnaire for All Subjects

Name: _____ Date: _____ I.D: _____

GODIN-SHEPHARD LEISURE-TIME EXERCISE QUESTIONNAIRE

1. Considering a **7-day period** (a week), how many times on the average do you do the following kinds of exercise for **more than 15 minutes** during your **free-time** (write on each line the appropriate number)?

Times Per Week

(a) STRENUOUS EXERCISE (HEART BEATS RAPIDLY)
(i.e. running, jogging, hockey, football, soccer, squash, basketball,

cross country skiing, judo, roller skating, vigorous swimming,

vigorous long distance bicycling) _____

(b) MODERATE EXERCISE (NOT EXHAUSTING)
(i.e. fast walking, baseball, tennis, easy bicycling, volleyball,

badminton, easy swimming, alpine skiing, popular and folk dancing)

_____

(c) MILD EXERCISE (MINIMAL EFFORT)

(i.e. yoga, archery, fishing from river bank, bowling, horseshoes,

golf, snow-mobiling, easy walking)

_____

2. Considering a **7-day period** (a week), during your leisure-time, how often do you engage in any regular activity long enough to work up a sweat (heart beats rapidly)?

1. OFTEN	**2. SOMETIMES**	**3. NEVER/RARELY**
☐	☐	☐

Appendix I: Training History Questionnaire

Name: _____ Date: _____ I.D: _____

TRAINING HISTORY QUESTIONNAIRE FOR ATHELTES

Please fill in the table below to the best of your knowledge.

If you have any difficulties, discuss the matter with one of the investigators.

Activity/Sport	Level of Competition	# of years	Sessions/ week	Min/session	Intensity (light, moderate, intense, very intense)	Seasonal length
Soccer						
Swimming						
Hockey						
Gymnastics						
Running						
Resistance						
Other						

Appendix J: Descriptive statistics – Control boys group

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
Age_y	18	5.60	7.30	12.90	9.9389	1.29439	1.675
Height	18	36.50	121.60	158.10	140.3333	9.14941	83.712
Sitting_height	18	19.00	139.50	158.50	147.5222	4.25435	18.099
Leg_Length	18	23.30	57.50	80.80	68.4500	5.83441	34.040
Yrs_PHV	18	3.60	-4.90	-1.30	-3.2833	.93132	.867
Weight	18	31.50	22.40	53.90	34.9222	8.10567	65.702
Tanner	18	1.50	1.00	2.50	1.4167	.54906	.301
Arm_length	18	7.00	21.00	28.00	24.8611	1.94638	3.788
Thigh_length	18	14.00	27.00	41.00	33.2500	3.67123	13.478
arm_circu	18	12.30	17.50	29.80	21.4278	3.06897	9.419
arm_CSA	18	24.53	19.47	44.01	28.0531	6.78209	45.997
SF_tri	18	18.70	5.10	23.80	10.9889	4.38995	19.272
SF_bic	18	13.20	3.00	16.20	6.6722	2.94515	8.674
SF_subsc	18	15.70	5.20	20.90	8.7444	4.23893	17.968
SF_suprail	18	18.40	3.60	22.00	7.8667	4.98456	24.846
BF	18	24.93	11.67	36.60	17.8894	6.31420	39.869
LBM	18	18.42	19.25	37.67	28.3050	4.84753	23.499
ant_thigh	18	31.00	9.20	40.20	18.1056	7.73088	59.766
pos_thigh	18	21.80	5.20	27.00	14.5778	5.24870	27.549
med_thigh	18	31.90	9.90	41.80	20.7611	8.50509	72.337
let_thigh	18	36.20	6.00	42.20	16.3944	9.02216	81.399
thigh_circu	18	22.80	30.00	52.80	38.9167	5.58678	31.212
thigh_CSA	18	13.50	10.30	23.80	15.6833	3.00710	9.043
BiU_Width	18	11.60	13.90	25.50	19.1889	3.40672	11.606
TriU_Width	18	11.40	14.70	26.10	18.4444	3.00181	9.011

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
HamU_Width	17	21.40	24.30	45.70	38.5882	5.89214	34.717
Quads_Width	18	16.70	20.00	36.70	27.4611	3.87346	15.004
BiU	18	358.96	151.75	510.71	297.8029	106.77902	11401.759
TriU	18	365.30	169.72	535.02	273.8744	94.65914	8960.354
HamU	17	1176.53	463.77	1640.30	1195.1616	336.29622	113095.150
QuadsU	18	743.69	314.16	1057.84	603.4079	170.83210	29183.607
EF_Frc_Pk	18	18.77	9.81	28.58	18.3415	4.38432	19.222
EF_Pfrc_Acsa	18	.33	.49	.82	.6535	.10374	.011
EF_Pfrc_kg	18	.41	.37	.78	.5337	.10913	.012
EF_Pfrc_LBM	18	.44	.44	.89	.6482	.11000	.012
EF_Pfrc_biU	18	.10	.04	.14	.0673	.02597	.001
EF_time_Pfrc	18	2600.00	371.00	2971.00	1556.4444	743.81815	553265.438
EF_RFD	18	162.82	30.02	192.85	99.0641	43.81786	1920.005
EF_RFD_Frc	18	6.03	2.79	8.83	5.1354	1.67037	2.790
EF_time_Prfd	18	86.00	68.00	154.00	93.6667	21.26859	452.353
EF_EMG_Pk	18	26.79	5.65	32.45	17.4269	7.65672	58.625
EF_time_Pag_EMG	18	2865.00	127.00	2992.00	1821.4444	924.63196	854944.261
EF_amp_AG_EMG_Prfd	18	13.35	1.76	15.10	6.4750	3.47223	12.056
EF_Q30	18	43.32	4.46	47.78	15.6867	13.38363	179.122
EF_Q30_EMG_Pk	18	1.98	.39	2.37	.9682	.58189	.339
EF_QpkAG	18	473.35	51.30	524.65	209.9702	122.85523	15093.409
EF_QpkAG_EMG_Pk	18	11.82	5.30	17.12	11.7640	3.35604	11.263
EF_AG_EMD	18	87.00	39.00	126.00	77.0000	23.68171	560.824
EF_PkAN_EMG	18	10.28	2.08	12.36	5.8250	2.76647	7.653
EF_time_PkAN_EMG	18	2237.00	717.00	2954.00	2095.0000	699.79325	489710.588
EF_AmpAN_EMGPkRFD	18	4.50	.66	5.15	1.9727	1.21475	1.476
EF_Q30AN	18	22.14	1.63	23.77	8.4456	5.45512	29.758

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
EF_QpkAN_EMG	18	123.36	21.40	144.76	54.8601	31.11688	968.260
EF_AN_EMD	18	123.00	16.00	139.00	69.9444	33.97486	1154.291
EF_AN_EMG_On_PkRFD_dela	18	126.00	106.00	232.00	163.6111	40.45497	1636.605
EF_Mmax_Frc	18	18.74	9.60	28.35	18.0701	4.33987	18.834
EF_Mmax_EMGag	18	16.30	4.04	20.34	10.2633	4.99188	24.919
EF_Mmax_EMGAn	18	8.17	1.04	9.22	3.4424	1.97251	3.891
EF_Cocontraction	18	.54	.13	.68	.3598	.16044	.026
EF_Coactivation	18	1.91	.29	2.20	.7958	.46154	.213
EE_Frc_Pk	18	21.30	12.57	33.87	21.5743	5.97894	35.748
EE_Pfrc_Acsa	18	.41	.57	.97	.7725	.12996	.017
EE_Pfrc_kg	18	.54	.45	.99	.6267	.15183	.023
EE_Pfrc_LBM	18	.60	.55	1.15	.7645	.17711	.031
EE_Pfrc_triU	18	.08	.04	.12	.0833	.02418	.001
EE_time_Pfrc	18	1946.00	937.00	2883.00	1867.0556	489.04703	239166.997
EE_RFD	18	134.33	40.49	174.82	105.1478	43.33980	1878.338
EE_RFD_Frc	18	5.93	2.55	8.48	4.8491	1.55727	2.425
EE_time_Prfd	18	73.00	57.00	130.00	83.1667	19.89753	395.912
EE_AG_EMG	18	7.90	2.62	10.52	7.5239	2.52925	6.397
EE_time_PkAG_EMG_Pk	18	2683.00	57.00	2740.00	1759.5556	726.38227	527631.203
EE_amp_AG_EMG_Prfd	18	7.74	1.07	8.81	3.4641	1.84789	3.415
EE_Q30	18	18.66	1.53	20.19	8.0715	5.87085	34.467
EE_Q30_EMG_Pk	18	3.09	.36	3.45	1.2287	.80880	.654
EE_QpkAG	18	229.75	32.99	262.74	96.4678	51.56544	2658.995
EE_QpkAG_EMG_Pk	18	19.10	5.87	24.97	12.8966	4.37014	19.098
EE_AG_EMD	18	94.00	26.00	120.00	67.8889	29.20493	852.928
EE_AG_EMG_On_pkRFD_dela	18	114.00	106.00	220.00	151.0556	35.92226	1290.408
EE_PkAN_EMG	18	4.92	.92	5.85	2.3060	1.26931	1.611

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
EE_time_PkAN_EMG	18	2900.00	32.00	2932.00	1152.2222	850.47928	723315.007
EE_AmpAN_EMGPkRFD	18	1.61	.30	1.90	.7110	.39056	.153
EE_Q30AN	18	46.18	2.24	48.42	9.7526	10.98534	120.678
EE_QpkAN_EMG	18	37.01	8.98	45.99	20.4663	11.08696	122.921
EE_AN_EMD	18	500.00	12.00	512.00	110.1667	149.65421	22396.382
EE_AN_EMG_On_PkRFD_dela	18	408.00	25.00	433.00	167.3333	104.14583	10846.353
EE_Mmax_Frc	18	21.72	12.07	33.79	21.3612	6.03055	36.368
EE_Mmax_EMGag	18	5.01	1.70	6.71	4.5675	1.53532	2.357
EE_Mmax_EMGan	18	1.23	.52	1.75	1.0222	.37149	.138
EE_Cocontraction	18	.51	.08	.59	.2550	.13835	.019
EE_Coactivation	18	.33	.03	.36	.1269	.08503	.007
KE_Frc_Pk	18	76.22	31.13	107.35	71.7674	23.95389	573.789
KE_Pfrc_Tcsa	18	8.71	1.31	10.02	4.7526	1.88364	3.548
KE_Pfrc_kg	18	2.32	.63	2.95	2.0753	.55031	.303
KE_Pfrc_LBM	18	2.97	.83	3.80	2.5342	.68351	.467
KE_Pfrc_QuaU	18	.17	.04	.21	.1243	.04177	.002
KE_time_Pfrc	18	2086.00	352.00	2438.00	1403.4444	572.50864	327766.144
KE_RFD	18	571.12	123.44	694.56	352.8616	155.06534	24045.258
KE_RFD_Frc	18	5.21	2.37	7.57	4.9915	1.51030	2.281
KE_time_Prfd	18	93.00	54.00	147.00	94.5000	22.25851	495.441
KE_AG_EMG	18	5.60	2.89	8.49	4.7842	1.38248	1.911
KE_amp_AG_EMG_Prfd	18	4.43	.96	5.38	2.8548	1.29183	1.669
KE_Q30	18	7.17	1.27	8.44	4.3548	2.17457	4.729
KE_Q30_EMG_PK	18	1.94	.34	2.27	.9429	.51041	.261
KE_QpkAG	18	134.21	26.30	160.52	79.5964	34.87545	1216.297
KE_QpkAG_EMG_Pk	18	17.75	6.66	24.41	16.3239	4.43272	19.649
KE_AG_EMD	18	74.00	29.00	103.00	68.0000	17.50294	306.353

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
KE_AG_EMG_On_pkRFD_dela	18	95.00	121.00	216.00	162.5000	27.11251	735.088
KE_PkAN_EMG	18	1.72	.21	1.93	.9022	.54595	.298
KE_time_PkAN_EMG	18	2721.00	45.00	2766.00	1349.1667	663.03529	439615.794
KE_AmpAN_EMGPkRFD	18	.37	.09	.45	.2519	.11377	.013
KE_Q30AN	18	10.07	.62	10.69	3.4309	3.06820	9.414
KE_QpkAN_EMG	18	11.34	2.50	13.84	7.9843	3.47850	12.100
KE_AN_EMD	18	111.00	2.00	113.00	40.6111	34.95567	1221.899
KE_AN_EMG_On_PkRFD_dela	18	159.00	8.00	167.00	112.4444	39.02521	1522.967
KE_Mmax_Frc	18	76.16	30.94	107.10	71.2272	23.95318	573.755
KE_Mmax_EMGag	18	2.99	1.80	4.79	2.8882	.79455	.631
KE_Mmax_EMGan	18	.90	.07	.97	.4396	.24708	.061
KE_Cocontaction	18	.30	.04	.34	.1544	.08562	.007
KE_Coactivation	18	.43	.05	.47	.1412	.10385	.011
KF_Frc_Pk	18	48.96	13.60	62.55	35.2945	12.34776	152.467
KF_Pfrc_Tcsa	18	2.87	1.09	3.95	2.2479	.69765	.487
KF_Pfrc_kg	18	.78	.61	1.39	.9997	.24634	.061
KF_Pfrc_LBM	18	.95	.71	1.66	1.2246	.31065	.097
KF_Pfrc_HamU	17	.04	.01	.05	.0300	.00937	.000
KF_time_Pfrc	18	1929.00	490.00	2419.00	1459.3889	563.22549	317222.958
KF_RFD	18	199.30	79.06	278.36	184.0652	57.58453	3315.978
KF_RFD_Frc	18	4.00	3.85	7.85	5.3473	1.02118	1.043
KF_time_Prfd	18	84.00	57.00	141.00	109.4444	27.22504	741.203
KF_AG_EMG	18	10.95	1.36	12.30	6.0742	2.98995	8.940
KF_time_PkAG_EMG_Pk	18	2825.00	31.00	2856.00	1458.8333	1000.99029	1001981.559
KF_amp_AG_EMG_Prfd	18	6.92	.80	7.72	3.2426	1.85412	3.438
KF_Q30	18	23.16	1.39	24.55	6.1315	5.39951	29.155
KF_Q30_EMG_Pk	18	3.73	.24	3.97	1.1320	.90122	.812

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
KF_QpkAG	18	210.74	21.61	232.35	102.3615	61.93797	3836.312
KF_QpkAG_EMG_Pk	18	13.50	8.68	22.18	16.3788	3.85399	14.853
KF_AG_EMD	18	99.00	34.00	133.00	88.3889	27.79577	772.605
KF_AG_EMG_On_pkRFD_dela	18	121.00	144.00	265.00	197.8333	37.75657	1425.559
KF_PkAN_EMG	18	.46	.16	.61	.3991	.13602	.019
KF_time_PkAN_EMG	18	2761.00	117.00	2878.00	1627.9444	825.21836	680985.350
KF_AmpAN_EMGPkRFD	18	.35	.09	.44	.1866	.08252	.007
KF_Q30AN	18	7.12	.60	7.73	2.1306	1.71596	2.945
KF_QpkAN_EMG	18	8.05	3.22	11.27	5.6844	2.11852	4.488
KF_AN_EMD	18	139.00	8.00	147.00	53.1111	39.92624	1594.105
KF_AN_EMD_On_PkRFD_dela	18	228.00	49.00	277.00	143.2222	62.28734	3879.712
KF_Mmax_Frc	18	48.75	13.21	61.96	34.9990	12.32189	151.829
KF_Mmax_EMGag	18	7.01	.76	7.77	3.7286	1.91406	3.664
KF_Mmax_EMGan	18	.30	.09	.40	.2389	.09111	.008
KF_Cocontraction	18	.44	.02	.47	.0941	.10174	.010
KF_Coactivation	18	.09	.04	.13	.0849	.02957	.001

Appendix K: Descriptive statistics – Endurance-trained boys group

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
Age_y	12	2.10	9.70	11.80	10.7083	.71790	.515
Height	12	22.00	135.60	157.60	145.9917	7.21859	52.108
Sitting_height	12	13.50	144.70	158.20	151.6167	4.05504	16.443
Leg_Length	12	10.40	65.10	75.50	70.3333	3.67011	13.470
Yrs_PHV	12	2.40	-3.70	-1.30	-2.5250	.77709	.604
Weight	12	37.90	28.30	66.20	41.5750	12.64725	159.953
Tanner	12	1.00	1.00	2.00	1.4167	.51493	.265
Arm_length	12	5.00	25.00	30.00	26.8750	1.61139	2.597
Thigh_length	12	8.00	31.00	39.00	35.0833	2.31432	5.356
arm_circu	12	12.50	19.20	31.70	23.8917	4.35315	18.950
arm_CSA	12	25.94	25.09	51.03	35.1896	9.11173	83.024
SF_tri	12	19.60	5.60	25.20	12.2167	7.18456	51.618
SF_bic	12	12.00	3.40	15.40	7.0000	4.22546	17.855
SF_subsc	12	28.80	4.60	33.40	11.3250	8.93238	79.788
SF_suprail	12	36.80	3.00	39.80	12.3250	12.93657	167.355
BF	12	37.35	9.35	46.70	20.0992	12.03786	144.910
LBM	12	17.28	24.69	41.97	31.9442	5.24470	27.507
ant_thigh	12	24.40	6.80	31.20	16.2083	6.94111	48.179
pos_thigh	11	19.00	5.20	24.20	13.5182	5.80118	33.654
med_thigh	11	51.60	7.60	59.20	21.8909	14.71580	216.555
let_thigh	12	32.60	5.60	38.20	17.6833	10.39072	107.967
thigh_circu	11	17.10	34.60	51.70	40.3455	5.22061	27.255
thigh_CSA	11	10.90	11.20	22.10	17.8545	3.44887	11.895
BiU_Width	12	19.30	15.70	35.00	23.7033	5.37179	28.856

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
TriU_Width	12	14.60	16.60	31.20	22.8575	4.73905	22.459
HamU_Width	12	33.78	17.80	51.58	40.4933	8.99178	80.852
Quads_Width	12	13.30	23.90	37.20	29.8967	3.85608	14.869
BiU	12	768.52	193.59	962.11	462.0493	216.35512	46809.540
TriU	12	548.11	216.42	764.54	426.5124	177.68516	31572.017
HamU	12	1840.70	248.85	2089.55	1346.0346	510.64911	260762.516
QuadsU	12	638.24	448.63	1086.87	712.7024	183.71199	33750.096
EF_Frc_Pk	11	31.26	12.85	44.11	25.6025	7.95498	63.282
EF_Pfrc_Acsa	11	.46	.49	.96	.7285	.12435	.015
EF_Pfrc_kg	11	.48	.40	.88	.6190	.12952	.017
EF_Pfrc_LBM	11	.57	.48	1.05	.7914	.17137	.029
EF_Pfrc_biU	11	.06	.03	.09	.0601	.01850	.000
EF_time_Pfrc	11	1613.00	603.00	2216.00	1474.1818	439.29439	192979.564
EF_RFD	11	213.52	85.25	298.77	152.5796	66.16368	4377.633
EF_RFD_Frc	11	4.44	3.26	7.69	5.8645	1.44276	2.082
EF_time_Prfd	11	31.00	67.00	98.00	79.2727	11.05523	122.218
EF_EMG_Pk	11	27.27	7.77	35.04	20.0116	8.49654	72.191
EF_time_Pag_EMG	11	1793.00	915.00	2708.00	1934.8182	588.06187	345816.764
EF_amp_AG_EMG_Prfd	11	17.31	3.08	20.39	8.3779	4.54755	20.680
EF_Q30	11	46.40	5.18	51.58	18.8782	13.24260	175.367
EF_Q30_EMG_Pk	11	1.70	.41	2.11	.9494	.51793	.268
EF_QpkAG	11	379.59	96.90	476.49	239.4006	112.61169	12681.393
EF_QpkAG_EMG_Pk	11	8.79	8.39	17.18	12.1105	2.76549	7.648
EF_AG_EMD	11	60.00	41.00	101.00	67.3636	19.92623	397.055
EF_AG_EMG_On_pkRFD_dela	11	64.00	115.00	179.00	146.6364	21.59293	466.255
EF_PkAN_EMG	11	7.07	1.59	8.65	5.2528	2.45627	6.033
EF_time_PkAN_EMG	11	1618.00	1263.00	2881.00	2146.7273	527.85341	278629.218

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
EF_AmpAN_EMGPkRFD	11	2.60	.35	2.95	1.6855	.84411	.713
EF_Q30AN	11	18.45	.83	19.28	6.1806	5.00023	25.002
EF_QpkAN_EMG	11	78.59	14.74	93.33	52.0049	25.08943	629.480
EF_AN_EMD	11	99.00	16.00	115.00	63.2727	36.30727	1318.218
EF_AN_EMG_On_PkRFD_dela	11	119.00	86.00	205.00	142.5455	37.16817	1381.473
EF_Mmax_Frc	11	31.14	12.75	43.88	25.4214	7.93458	62.958
EF_Mmax_EMGag	11	19.75	4.61	24.36	12.2573	5.92118	35.060
EF_Mmax_EMGAn	11	3.67	.90	4.57	2.8389	1.38282	1.912
EF_Cocontraction	11	.82	.09	.91	.2798	.22607	.051
EF_Coactivation	11	1.49	.18	1.67	.6129	.41720	.174
EE_Frc_Pk	11	47.48	13.73	61.21	28.6580	13.81453	190.841
EE_Pfrc_Acsa	11	.70	.52	1.22	.7985	.25209	.064
EE_Pfrc_kg	11	.64	.40	1.03	.6805	.20992	.044
EE_Pfrc_LBM	11	.95	.51	1.46	.8643	.27616	.076
EE_Pfrc_triU	11	.08	.04	.12	.0740	.02372	.001
EE_time_Pfrc	11	1956.00	926.00	2882.00	1714.7273	549.58313	302041.618
EE_RFD	11	268.18	61.23	329.41	155.2424	81.17423	6589.255
EE_RFD_Frc	11	5.84	4.24	10.08	5.4225	1.63875	2.686
EE_time_Prfd	11	70.00	63.00	133.00	85.2727	21.50856	462.618
EE_AG_EMG	11	34.26	1.26	35.52	10.7471	9.31009	86.678
EE_time_PkAG_EMG_Pk	11	1796.00	1105.00	2901.00	1861.1818	553.66142	306540.964
EE_amp_AG_EMG_Prfd	11	10.29	.39	10.68	4.4683	3.19088	10.182
EE_Q30	11	36.82	.87	37.70	9.9148	11.27105	127.037
EE_Q30_EMG_Pk	11	2.37	.29	2.66	.9541	.68568	.470
EE_QpkAG	11	410.51	11.41	421.92	134.0624	113.29259	12835.211
EE_QpkAG_EMG_Pk	11	14.24	5.35	19.59	12.8295	4.33554	18.797
EE_AG_EMD	11	100.00	32.00	132.00	68.2727	30.46667	928.218

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
EE_AG_EMG_On_pkRFD_dela	11	122.00	99.00	221.00	153.5455	40.23025	1618.473
EE_PkAN_EMG	11	14.90	.96	15.86	3.1115	4.27876	18.308
EE_time_PkAN_EMG	11	2300.00	463.00	2763.00	1790.4545	703.90487	495482.073
EE_AmpAN_EMGPkRFD	11	.65	.22	.87	.5630	.20321	.041
EE_Q30AN	11	56.83	1.12	57.95	9.3840	16.63308	276.659
EE_QpkAN_EMG	11	19.90	5.72	25.62	15.7217	5.43055	29.491
EE_AN_EMD	11	126.00	21.00	147.00	81.8182	52.24523	2729.564
EE_AN_EMG_On_PkRFD_dela	11	229.00	6.00	235.00	144.0000	68.90428	4747.800
EE_Mmax_Frc	11	47.23	13.56	60.79	28.4469	13.74816	189.012
EE_Mmax_EMGag	11	20.55	.54	21.09	6.6476	5.54439	30.740
EE_Mmax_EMGan	11	2.41	.28	2.69	1.0198	.63235	.400
EE_Cocontraction	11	.41	.10	.51	.2025	.11707	.014
EE_Coactivation	11	.14	.04	.18	.0915	.05047	.003
KE_Frc_Pk	12	114.98	48.13	163.11	96.9054	32.48297	1055.144
KE_Pfrc_Tcsa	11	3.08	3.61	6.69	5.0910	1.06369	1.131
KE_Pfrc_kg	12	1.89	1.21	3.10	2.3855	.59271	.351
KE_Pfrc_LBM	12	2.10	1.78	3.89	2.9778	.60232	.363
KE_Pfrc_QuaU	12	.17	.07	.24	.1416	.05131	.003
KE_time_Pfrc	12	2171.00	690.00	2861.00	1596.9167	631.07606	398256.992
KE_RFD	12	612.02	100.64	712.66	468.0413	185.32083	34343.809
KE_RFD_Frc	12	4.18	2.09	6.27	4.7430	1.24005	1.538
KE_time_Prfd	12	156.00	70.00	226.00	104.5833	41.15041	1693.356
KE_AG_EMG	12	7.45	1.73	9.18	5.3253	2.17520	4.732
KE_amp_AG_EMG_Prfd	12	4.24	.70	4.94	2.8937	1.33283	1.776
KE_Q30	12	15.66	1.03	16.69	5.8661	4.20735	17.702
KE_Q30_EMG_PK	12	2.32	.46	2.78	1.0624	.58901	.347
KE_QpkAG	12	122.85	19.97	142.82	87.9692	41.79034	1746.433

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
KE_QpkAG_EMG_Pk	12	9.88	11.55	21.43	15.9384	2.98867	8.932
KE_AG_EMD	12	68.94	27.00	95.94	59.9953	19.60975	384.542
KE_AG_EMG_On_pkRFD_dela	12	273.07	3.93	277.00	151.0776	62.42310	3896.643
KE_PkAN_EMG	12	1.28	.29	1.57	.8472	.47438	.225
KE_time_PkAN_EMG	12	2989.89	.11	2990.00	1270.6755	1065.56882	1135436.914
KE_AmpAN_EMGPkRFD	12	.72	.06	.79	.3269	.23309	.054
KE_Q30AN	12	12.26	.44	12.71	4.9731	3.96256	15.702
KE_QpkAN_EMG	12	19.08	1.55	20.63	10.5970	6.91017	47.751
KE_AN_EMD	12	1590.00	4.00	1594.00	243.0833	454.46381	206537.356
KE_AN_EMG_On_PkRFD_dela	12	1453.00	60.00	1513.00	268.8333	401.02909	160824.333
KE_Mmax_Frc	12	115.57	46.84	162.40	96.2595	32.55955	1060.124
KE_Mmax_EMGag	12	4.57	.99	5.56	3.3121	1.43037	2.046
KE_Mmax_EMGan	12	.68	.17	.85	.4225	.24084	.058
KE_Cocontaction	12	.83	.03	.86	.1767	.22045	.049
KE_Coactivation	12	.58	.04	.62	.1553	.17400	.030
KF_Frc_Pk	12	57.28	21.92	79.20	47.4949	16.71400	279.358
KF_Pfrc_Tcsa	11	2.14	1.44	3.59	2.5329	.60121	.361
KF_Pfrc_kg	12	1.05	.51	1.56	1.1675	.32176	.104
KF_Pfrc_LBM	12	1.22	.89	2.11	1.4578	.35485	.126
KF_Pfrc_HamU	12	.10	.01	.12	.0420	.02622	.001
KF_time_Pfrc	12	1680.00	843.00	2523.00	1458.8333	566.31839	320716.515
KF_RFD	12	281.41	85.85	367.26	237.8585	86.50150	7482.510
KF_RFD_Frc	12	2.76	3.55	6.31	5.0014	.90275	.815
KF_time_Prfd	12	153.00	65.00	218.00	116.8333	41.86740	1752.879
KF_AG_EMG	12	8.09	2.14	10.23	6.0673	2.43299	5.919
KF_time_PkAG_EMG_Pk	12	2528.00	41.00	2569.00	1314.1667	828.02205	685620.515
KF_amp_AG_EMG_Prfd	12	6.40	1.23	7.63	3.5401	1.76526	3.116

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
KF_Q30	12	10.60	2.30	12.90	5.9790	3.48867	12.171
KF_Q30_EMG_Pk	12	2.14	.33	2.47	1.0956	.63990	.409
KF_QpkAG	12	159.11	38.05	197.16	109.0670	49.12409	2413.176
KF_QpkAG_EMG_Pk	12	7.35	13.49	20.84	17.8085	1.99892	3.996
KF_AG_EMD	12	57.00	62.00	119.00	87.8333	18.03952	325.424
KF_AG_EMG_On_pkRFD_dela y	12	163.00	143.00	306.00	204.6667	45.96507	2112.788
KF_PkAN_EMG	12	.58	.17	.76	.4639	.15184	.023
KF_time_PkAN_EMG	12	2140.00	322.00	2462.00	1497.7500	645.16821	416242.023
KF_AmpAN_EMGPkRFD	12	.32	.06	.38	.1911	.09337	.009
KF_Q30AN	12	2.47	.58	3.05	1.6462	.84648	.717
KF_QpkAN_EMG	12	9.18	1.25	10.44	5.8078	2.93414	8.609
KF_AN_EMD	12	120.00	2.00	122.00	43.0000	33.65061	1132.364
KF_AN_EMD_On_PkRFD_dela	12	201.00	49.00	250.00	155.3333	62.56100	3913.879
KF_Mmax_Frc	12	57.09	21.78	78.87	47.1846	16.66169	277.612
KF_Mmax_EMGag	12	4.39	1.37	5.76	3.8207	1.52201	2.317
KF_Mmax_EMGan	12	.35	.04	.39	.2432	.09712	.009
KF_Cocontraction	12	.15	.01	.16	.0764	.04729	.002
KF_Coactivation	12	.20	.02	.23	.0896	.06738	.005

Appendix L: Descriptive statistics – Control adults group

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
Age_y	20	16.30	18.90	35.20	22.8400	4.46193	19.909
Height	20	25.10	169.50	194.60	180.5750	7.40056	54.768
Weight	20	56.80	62.50	119.30	80.4550	12.46306	155.328
Arm_length	20	10.30	29.20	39.50	33.6700	2.34186	5.484
Thigh_length	20	10.70	36.80	47.50	43.0350	2.59215	6.719
arm_circu	20	9.30	27.50	36.80	31.8200	2.83801	8.054
arm_CSA	20	36.92	50.56	87.48	68.3318	11.24506	126.451
SF_tri	20	14.40	3.80	18.20	11.1750	3.74459	14.022
SF_bic	20	7.80	3.00	10.80	5.4200	1.95760	3.832
SF_subsc	20	25.20	7.00	32.20	15.4250	5.89396	34.739
SF_suprail	20	27.40	5.20	32.60	16.0550	7.63148	58.239
BF	20	19.05	8.29	27.34	17.9225	4.82172	23.249
LBM	20	35.11	54.68	89.79	65.6855	8.13282	66.143
ant_thigh	20	22.00	4.40	26.40	16.6900	6.03751	36.451
pos_thigh	17	27.80	4.20	32.00	17.4706	7.00890	49.125
med_thigh	20	50.40	7.60	58.00	26.1050	9.90329	98.075
let_thigh	19	19.80	3.80	23.60	14.9421	5.28397	27.920
thigh_circu	20	21.80	44.80	66.60	53.9250	4.89209	23.933
thigh_CSA	18	43.00	18.30	61.30	37.2722	9.05628	82.016
BiU_Width	20	13.60	24.50	38.10	31.8150	4.13092	17.064
TriU_Width	20	23.80	23.30	47.10	31.2150	5.39115	29.064
HamU_Width	20	24.00	39.70	63.70	52.8300	7.25622	52.653
Quads_Width	20	32.70	29.70	62.40	40.5650	7.24665	52.514

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
BiU	20	668.78	469.51	1138.30	807.2232	207.54361	43074.351
TriU	20	1317.80	426.75	1744.56	786.5536	295.39851	87260.278
HamU	20	1949.04	1237.86	3186.90	2231.4826	596.38431	355674.248
BiU	20	668.78	469.51	1138.30	807.2232	207.54361	43074.351
QuadsU	20	2365.36	692.79	3058.15	1331.3628	518.31656	268652.060
EF_Frc_Pk	20	43.66	45.14	88.81	71.4057	8.97618	80.572
EF_Pfrc_Acsa	20	.78	.73	1.51	1.0753	.24214	.059
EF_Pfrc_kg	20	.78	.54	1.31	.9045	.16791	.028
EF_Pfrc_LBM	20	.72	.71	1.43	1.0975	.16206	.026
EF_Pfrc_biU	20	.11	.06	.16	.0940	.02748	.001
EF_time_Pfrc	20	2452.00	325.00	2777.00	1215.9500	667.82021	445983.839
EF_RFD	20	547.12	300.98	848.10	567.4069	138.86633	19283.859
EF_RFD_Frc	20	7.97	4.72	12.69	8.0101	2.02186	4.088
EF_time_Prfd	20	40.00	49.00	89.00	69.0000	12.23025	149.579
EF_EMG_Pk	20	70.21	4.55	74.76	34.4555	18.86358	355.835
EF_time_Pag_EMG	20	2709.00	124.00	2833.00	1451.7000	837.84191	701979.063
EF_amp_AG_EMG_Prfd	20	55.51	3.16	58.67	19.2004	14.94515	223.358
EF_Q30	20	352.73	.74	353.48	60.3726	82.48683	6804.077
EF_Q30_EMG_Pk	20	5.00	.16	5.16	1.5378	1.30795	1.711
EF_QpkAG	20	1626.15	80.52	1706.67	552.9187	414.88394	172128.686
EF_QpkAG_EMG_Pk	20	16.02	8.90	24.92	15.8617	5.13345	26.352
EF_AG_EMD	20	42.00	28.00	70.00	53.6000	10.68398	114.147
EF_AG_EMG_On_pkRFD_dela	20	48.00	103.00	151.00	122.6000	14.23265	202.568
EF_PkAN_EMG	20	10.45	.75	11.21	4.9646	2.77453	7.698
EF_time_PkAN_EMG	20	2953.00	27.00	2980.00	1761.0000	924.39306	854502.526
EF_AmpAN_EMGPkRFD	20	10.18	.50	10.68	2.3904	2.13162	4.544
EF_Q30AN	20	18.32	.50	18.82	4.7442	4.06468	16.522

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
EF_QpkAN_EMG	20	244.82	15.33	260.14	63.8267	51.45881	2648.009
EF_AN_EMD	20	117.00	28.00	145.00	83.4500	35.29496	1245.734
EF_AN_EMG_On_PkRFD_dela	20	127.00	90.00	217.00	152.4500	37.40739	1399.313
EF_Mmax_Frc	20	43.61	44.97	88.58	71.0237	8.98434	80.718
EF_Mmax_EMGag	20	49.58	3.07	52.65	22.6195	12.88805	166.102
EF_Mmax_EMGAn	20	5.64	.44	6.08	2.7471	1.41432	2.000
EF_Cocontraction	20	.36	.05	.41	.1401	.07795	.006
EF_Coactivation	20	2.13	.14	2.27	.6601	.49757	.248
EE_Frc_Pk	20	30.02	39.22	69.24	59.0741	6.78942	46.096
EE_Pfrc_Acsa	20	.61	.67	1.28	.8830	.16238	.026
EE_Pfrc_kg	20	.44	.52	.95	.7468	.12373	.015
EE_Pfrc_LBM	20	.44	.69	1.12	.9076	.12641	.016
EE_Pfrc_triU	20	.09	.04	.13	.0825	.02507	.001
EE_time_Pfrc	20	2388.00	562.00	2950.00	1794.8000	761.53416	579934.274
EE_RFD	20	396.23	326.31	722.54	518.5054	113.34438	12846.948
EE_RFD_Frc	20	7.38	5.30	12.68	8.8512	1.99116	3.965
EE_time_Prfd	20	35.00	50.00	85.00	63.1000	8.21360	67.463
EE_AG_EMG	20	42.71	2.40	45.11	9.2652	9.52964	90.814
EE_time_PkAG_EMG_Pk	20	2513.00	324.00	2837.00	2038.6500	660.93931	436840.766
EE_amp_AG_EMG_Prfd	20	15.63	.67	16.29	4.1713	3.61891	13.097
EE_Q30	20	20.76	.76	21.52	7.4385	6.88183	47.360
EE_Q30_EMG_Pk	20	3.29	.17	3.46	.9486	.92706	.859
EE_QpkAG	20	755.38	21.10	776.48	140.4213	163.95702	26881.904
EE_QpkAG_EMG_Pk	20	18.08	6.39	24.47	14.5938	4.81184	23.154
EE_AG_EMD	20	79.00	24.00	103.00	60.2500	22.83781	521.566
EE_AG_EMG_On_pkRFD_dela	20	75.00	87.00	162.00	123.3500	23.98964	575.503
EE_PkAN_EMG	20	4.19	.47	4.67	1.7712	1.16825	1.365

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
EE_time_PkAN_EMG	20	2880.00	27.00	2907.00	1852.8500	764.81345	584939.608
EE_AmpAN_EMGPkRFD	20	1.48	.20	1.68	.5848	.31481	.099
EE_Q30AN	20	18.53	.50	19.03	5.4126	5.94337	35.324
EE_QpkAN_EMG	20	25.49	8.23	33.72	15.2421	6.25619	39.140
EE_AN_EMD	20	1052.00	.00	1052.00	97.9500	227.86664	51923.208
EE_AN_EMG_On_PkRFD_dela	20	942.00	53.00	995.00	153.4500	202.57591	41036.997
EE_Mmax_Frc	20	30.03	39.11	69.14	58.7936	6.78549	46.043
EE_Mmax_EMGag	20	28.55	1.56	30.12	5.9942	6.39114	40.847
EE_Mmax_EMGan	20	1.17	.28	1.46	.7436	.30380	.092
EE_Cocontraction	20	.28	.04	.33	.1730	.07793	.006
EE_Coactivation	20	.14	.01	.14	.0451	.03274	.001
KE_Frc_Pk	19	156.02	144.04	300.06	226.1892	42.53648	1809.352
KE_Pfrc_Tcsa	18	10.29	.00	10.29	5.9146	2.18324	4.767
KE_Pfrc_kg	19	1.77	2.08	3.85	2.8451	.53831	.290
KE_Pfrc_LBM	19	1.94	2.46	4.40	3.4728	.60735	.369
KE_Pfrc_QuaU	19	.22	.07	.29	.1842	.05744	.003
KE_time_Pfrc	19	1942.00	353.00	2295.00	1266.5789	610.02608	372131.813
KE_RFD	19	1209.40	891.99	2101.39	1343.4589	364.31503	132725.439
KE_RFD_Frc	19	4.69	3.50	8.18	5.9916	1.33361	1.779
KE_time_Prfd	19	44.00	61.00	105.00	79.3158	11.99098	143.784
KE_AG_EMG	19	11.83	1.97	13.80	6.2896	3.14860	9.914
KE_amp_AG_EMG_Prfd	19	6.36	.96	7.32	3.1652	1.94551	3.785
KE_Q30	19	22.94	1.33	24.27	7.1273	6.18074	38.202
KE_Q30_EMG_PK	19	1.99	.19	2.18	1.0973	.66821	.446
KE_QpkAG	19	239.21	25.69	264.90	100.6076	63.49164	4031.189
KE_QpkAG_EMG_Pk	19	16.25	8.35	24.60	15.5952	4.26094	18.156
KE_AG_EMD	19	47.00	36.00	83.00	58.9474	15.50797	240.497

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
KE_AG_EMG_On_pkRFD_dela	19	63.00	108.00	171.00	138.2632	19.54153	381.871
KE_PkAN_EMG	19	5.83	.13	5.96	.9300	1.31216	1.722
KE_time_PkAN_EMG	19	2537.00	29.00	2566.00	1024.1579	881.09284	776324.585
KE_AmpAN_EMGPkRFD	19	1.01	.03	1.04	.2913	.23197	.054
KE_Q30AN	19	11.28	.34	11.63	2.3407	2.76777	7.661
KE_QpkAN_EMG	19	34.42	1.31	35.73	10.0371	8.23022	67.737
KE_AN_EMD	19	146.00	4.00	150.00	61.5789	54.23438	2941.368
KE_AN_EMG_On_PkRFD_dela	19	166.00	68.00	234.00	137.7368	55.76024	3109.205
KE_Mmax_Frc	19	156.56	142.92	299.48	225.3980	42.57043	1812.242
KE_Mmax_EMGag	19	6.37	1.37	7.74	3.7300	1.89650	3.597
KE_Mmax_EMGan	19	1.62	.04	1.67	.3926	.35030	.123
KE_Cocontaction	19	.32	.02	.34	.1115	.07806	.006
KE_Coactivation	19	.24	.04	.27	.1314	.06877	.005
KF_Frc_Pk	20	72.12	63.08	135.20	101.4661	20.29070	411.712
KF_Pfrc_Tcsa	18	2.28	1.72	4.00	2.8597	.66843	.447
KF_Pfrc_kg	20	.95	.87	1.82	1.2774	.27080	.073
KF_Pfrc_LBM	20	1.06	1.07	2.14	1.5509	.28870	.083
KF_Pfrc_HamU	20	.06	.03	.09	.0492	.01805	.000
KF_time_Pfrc	20	2338.00	270.00	2608.00	1362.9000	696.10729	484565.358
KF_RFD	20	461.36	393.39	854.75	621.6144	150.34059	22602.292
KF_RFD_Frc	20	5.55	3.80	9.34	6.2442	1.49555	2.237
KF_time_Prfd	20	122.00	51.00	173.00	97.8500	42.26766	1786.555
KF_AG_EMG	20	12.55	1.03	13.58	5.2513	2.95396	8.726
KF_time_PkAG_EMG_Pk	20	2884.00	11.00	2895.00	1033.5000	935.26396	874718.684
KF_amp_AG_EMG_Prfd	20	9.35	.78	10.13	3.5940	2.31920	5.379
KF_Q30	20	24.00	1.52	25.53	7.4121	6.12048	37.460
KF_Q30_EMG_Pk	20	2.88	.41	3.29	1.4710	.86389	.746

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
KF_QpkAG	20	219.06	25.79	244.85	107.4405	61.41197	3771.431
KF_QpkAG_EMG_Pk	20	14.32	14.36	28.68	20.6289	3.52796	12.447
KF_AG_EMD	20	89.00	33.00	122.00	73.6500	23.94132	573.187
KF_AG_EMG_On_pkRFD_dela	20	183.00	112.00	295.00	171.5000	53.35137	2846.368
KF_PkAN_EMG	20	.45	.13	.58	.3440	.13342	.018
KF_time_PkAN_EMG	20	2569.00	86.00	2655.00	1557.6000	873.05606	762226.884
KF_AmpAN_EMGPkRFD	20	.40	.05	.46	.1737	.08365	.007
KF_Q30AN	20	2.17	.38	2.55	1.2225	.71242	.508
KF_QpkAN_EMG	20	7.67	1.58	9.25	4.7654	1.74131	3.032
KF_AN_EMD	20	126.00	4.00	130.00	56.0000	41.29101	1704.947
KF_AN_EMD_On_PkRFD_dela	20	122.00	91.00	213.00	153.4500	40.80696	1665.208
KF_Mmax_Frc	20	73.01	61.93	134.93	100.4432	21.19383	449.178
KF_Mmax_EMGag	20	8.31	.55	8.86	3.1030	1.88202	3.542
KF_Mmax_EMGan	20	.31	.08	.39	.1783	.07865	.006
KF_Cocontraction	20	.23	.02	.25	.0777	.06218	.004
KF_Coactivation	19	.08	.02	.10	.0549	.02343	.001

Appendix M: Descriptive statistics – Endurance adults group

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
Age_y	15	17.20	18.43	35.63	24.5571	5.90567	34.877
Height	15	19.60	170.80	190.40	179.2000	5.76405	33.224
Weight	15	26.30	58.60	84.90	74.7133	6.00760	36.091
Arm_length	15	5.00	30.00	35.00	33.4667	1.35576	1.838
Thigh_length	15	7.50	38.50	46.00	42.5400	2.20771	4.874
arm_circu	15	4.50	29.30	33.80	30.8867	1.31793	1.737
arm_CSA	15	28.47	54.19	82.66	67.3767	7.08416	50.185
SF_tri	15	9.60	4.00	13.60	6.9733	2.29268	5.256
SF_bic	15	4.80	3.20	8.00	4.6533	1.28834	1.660
SF_subsc	15	9.20	8.20	17.40	12.0133	2.81878	7.946
SF_suprail	15	18.40	5.20	23.60	10.9600	4.98065	24.807
BF	15	11.70	9.20	20.90	14.8475	3.78672	14.339
LBM	15	21.10	52.05	73.15	63.5507	5.14907	26.513
ant_thigh	15	14.60	4.60	19.20	10.8533	3.87701	15.031
pos_thigh	13	14.40	4.80	19.20	10.0462	4.11595	16.941
med_thigh	15	27.20	.00	27.20	14.5733	7.28398	53.056
let_thigh	15	14.60	3.80	18.40	9.9867	3.75953	14.134
thigh_circu	15	8.80	47.60	56.40	52.6867	2.62892	6.911
thigh_CSA	14	22.10	27.10	49.20	41.1143	5.56056	30.920
BiU_Width	15	20.37	18.53	38.90	31.3213	5.53293	30.613
TriU_Width	15	19.30	26.20	45.50	34.5540	5.09625	25.972
HamU_Width	15	20.50	43.50	64.00	53.6407	6.16847	38.050
Quads_Width	15	17.00	33.60	50.60	42.4707	5.14353	26.456
BiU	15	918.80	269.68	1188.47	792.9367	256.69534	65892.500

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
TriU	15	1086.84	539.13	1625.97	956.7871	282.49278	79802.168
HamU	15	1730.82	1486.17	3216.99	2287.7348	527.92431	278704.075
QuadsU	15	1124.22	886.68	2010.90	1436.0611	342.14099	117060.458
EF_Frc_Pk	15	22.80	54.71	77.51	66.9440	7.56993	57.304
EF_Pfrc_Acsa	15	.45	.83	1.28	.9989	.11871	.014
EF_Pfrc_kg	15	.28	.73	1.01	.8981	.09251	.009
EF_Pfrc_LBM	15	.30	.91	1.21	1.0541	.09432	.009
EF_Pfrc_biU	15	.22	.05	.27	.0995	.05581	.003
EF_time_Pfrc	15	2605.00	342.00	2947.00	1171.8000	762.39193	581241.457
EF_RFD	15	438.05	301.74	739.79	505.4295	138.74007	19248.807
EF_RFD_Frc	15	6.25	4.60	10.85	7.5382	1.82582	3.334
EF_time_Prfd	15	37.00	50.00	87.00	70.8000	10.75839	115.743
EF_EMG_Pk	15	53.23	10.46	63.70	33.9797	13.89495	193.070
EF_time_Pag_EMG	15	2226.00	329.00	2555.00	1647.3333	834.68349	696696.524
EF_amp_AG_EMG_Prfd	15	29.36	6.06	35.42	18.1062	8.53979	72.928
EF_Q30	15	124.02	15.35	139.37	68.3421	40.28920	1623.219
EF_Q30_EMG_Pk	15	4.32	.29	4.62	2.2044	1.22338	1.497
EF_QpkAG	15	751.33	167.68	919.00	523.6593	206.18462	42512.097
EF_QpkAG_EMG_Pk	15	12.48	10.07	22.55	15.9518	3.75172	14.075
EF_AG_EMD	15	53.00	33.00	86.00	47.8667	15.27775	233.410
EF_AG_EMG_On_pkRFD_dela	15	66.00	93.00	159.00	118.6667	19.21929	369.381
EF_PkAN_EMG	15	6.97	2.07	9.04	3.8207	1.79842	3.234
EF_time_PkAN_EMG	15	2827.00	33.00	2860.00	2109.8000	936.94208	877860.457
EF_AmpAN_EMGPkRFD	15	2.06	.83	2.89	1.5225	.51096	.261
EF_Q30AN	15	9.52	1.32	10.84	4.1822	2.84885	8.116
EF_QpkAN_EMG	15	62.13	28.83	90.96	46.9745	16.45436	270.746
EF_AN_EMD	15	125.00	18.00	143.00	76.3333	36.43324	1327.381

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
EF_AN_EMG_On_PkRFD_dela	15	117.00	99.00	216.00	147.1333	36.17589	1308.695
EF_Mmax_Frc	15	22.62	54.60	77.22	66.4784	7.74897	60.047
EF_Mmax_EMGag	15	37.76	6.17	43.93	21.7927	9.30552	86.593
EF_Mmax_EMGAn	15	4.79	1.01	5.79	2.2747	1.18802	1.411
EF_Cocontraction	15	.21	.04	.25	.1158	.05998	.004
EF_Coactivation	15	1.09	.12	1.21	.3917	.26420	.070
EE_Frc_Pk	15	47.87	39.22	87.09	58.5238	12.12802	147.089
EE_Pfrc_Acsa	15	.68	.60	1.28	.8698	.16521	.027
EE_Pfrc_kg	15	.66	.52	1.18	.7869	.16824	.028
EE_Pfrc_LBM	15	.69	.65	1.34	.9205	.17372	.030
EE_Pfrc_triU	15	.09	.04	.13	.0655	.02278	.001
EE_time_Pfrc	15	1617.00	252.00	1869.00	943.1333	534.74251	285949.552
EE_RFD	15	338.05	361.77	699.82	466.5091	107.10763	11472.044
EE_RFD_Frc	15	8.15	4.25	12.40	8.2228	2.13243	4.547
EE_time_Prfd	15	36.00	55.00	91.00	68.8667	10.32242	106.552
EE_AG_EMG	15	16.09	5.52	21.61	10.5722	5.13151	26.332
EE_time_PkAG_EMG_Pk	15	2693.00	282.00	2975.00	1384.2667	934.85992	873963.067
EE_amp_AG_EMG_Prfd	15	10.81	2.25	13.06	6.0188	3.37315	11.378
EE_Q30	14	44.78	2.05	46.83	15.5452	12.67880	160.752
EE_Q30_EMG_Pk	14	2.60	.23	2.84	1.4490	.78935	.623
EE_QpkAG	15	310.74	68.70	379.44	181.2360	95.50339	9120.898
EE_QpkAG_EMG_Pk	15	11.77	12.45	24.22	16.9652	3.28795	10.811
EE_AG_EMD	15	70.00	28.00	98.00	46.7333	18.80147	353.495
EE_AG_EMG_On_pkRFD_dela	15	89.00	83.00	172.00	115.6000	24.00238	576.114
EE_PkAN_EMG	15	2.13	.47	2.60	1.1394	.55686	.310
EE_time_PkAN_EMG	15	2729.00	90.00	2819.00	1585.5333	1080.91634	1168380.124
EE_AmpAN_EMGPkRFD	15	.70	.17	.87	.4228	.17103	.029

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
EE_Q30AN	15	7.39	.89	8.28	3.1610	1.97303	3.893
EE_QpkAN_EMG	15	14.34	5.57	19.91	12.7175	4.44290	19.739
EE_AN_EMD	15	77.00	3.00	80.00	33.4000	23.17881	537.257
EE_AN_EMG_On_PkRFD_dela	15	82.00	72.00	154.00	101.8667	27.46652	754.410
EE_Mmax_Frc	15	47.69	39.08	86.77	58.0087	12.20940	149.069
EE_Mmax_EMGag	15	11.73	3.17	14.89	6.9286	3.61203	13.047
EE_Mmax_EMGan	15	.88	.22	1.09	.5628	.22705	.052
EE_Cocontraction	15	.32	.02	.35	.1039	.07835	.006
EE_Coactivation	15	.17	.01	.18	.0354	.04076	.002
KE_Frc_Pk	15	153.59	138.05	291.65	211.4198	39.55708	1564.763
KE_Pfrc_Tcsa	14	2.30	3.94	6.24	5.0786	.69294	.480
KE_Pfrc_kg	15	1.38	2.05	3.44	2.8270	.45165	.204
KE_Pfrc_LBM	15	1.50	2.49	3.99	3.3152	.47938	.230
KE_Pfrc_QuaU	15	.14	.10	.24	.1533	.03849	.001
KE_time_Pfrc	15	2103.00	345.00	2448.00	1231.2000	555.15496	308197.029
KE_RFD	15	1180.07	670.62	1850.69	1228.7591	358.91388	128819.175
KE_RFD_Frc	15	4.26	3.44	7.70	5.7921	1.24426	1.548
KE_time_Prfd	15	73.00	63.00	136.00	81.8667	18.52360	343.124
KE_AG_EMG	15	12.10	4.25	16.36	8.0998	3.69879	13.681
KE_amp_AG_EMG_Prfd	15	9.73	1.56	11.29	4.0860	2.43175	5.913
KE_Q30	15	27.71	4.19	31.90	15.2106	9.12369	83.242
KE_Q30_EMG_PK	15	3.65	.86	4.51	1.9476	1.16059	1.347
KE_QpkAG	15	230.85	73.46	304.31	131.7324	60.28803	3634.647
KE_QpkAG_EMG_Pk	15	11.28	11.56	22.85	16.6596	3.71728	13.818
KE_AG_EMD	15	56.00	36.00	92.00	53.6667	15.15476	229.667
KE_AG_EMG_On_pkRFD_dela	15	121.00	107.00	228.00	135.5333	31.88566	1016.695
KE_PkAN_EMG	15	1.80	.20	2.01	.6792	.46697	.218

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
KE_time_PkAN_EMG	15	2810.00	-29.00	2781.00	1272.9333	977.76235	956019.210
KE_AmpAN_EMGPkRFD	15	.83	.08	.91	.3085	.20898	.044
KE_Q30AN	15	9.97	.43	10.41	3.8361	3.30715	10.937
KE_QpkAN_EMG	15	19.33	2.07	21.40	8.8153	4.94895	24.492
KE_AN_EMD	15	1476.00	4.00	1480.00	143.8000	372.58541	138819.886
KE_AN_EMG_On_PkRFD_dela	15	1325.00	76.00	1401.00	214.6000	331.47178	109873.543
KE_Mmax_Frc	15	154.21	136.97	291.18	210.4581	39.86721	1589.394
KE_Mmax_EMGag	15	8.57	2.31	10.87	4.9853	2.55513	6.529
KE_Mmax_EMGan	15	1.15	.13	1.29	.4075	.31059	.096
KE_Cocontaction	15	.32	.02	.33	.1005	.08537	.007
KE_Coactivation	15	.32	.03	.35	.0983	.07642	.006
KF_Frc_Pk	15	68.56	74.43	142.99	101.8193	21.57632	465.537
KF_Pfrc_Tcsa	14	1.88	1.69	3.56	2.5359	.60678	.368
KF_Pfrc_kg	15	.90	1.01	1.91	1.3623	.26095	.068
KF_Pfrc_LBM	15	1.06	1.14	2.20	1.6012	.30298	.092
KF_Pfrc_HamU	15	.07	.02	.09	.0475	.01743	.000
KF_time_Pfrc	15	1053.00	259.00	1312.00	733.8000	266.33872	70936.314
KF_RFD	15	864.46	230.59	1095.06	636.0561	227.80186	51893.689
KF_RFD_Frc	15	5.41	3.10	8.50	6.1239	1.24272	1.544
KF_time_Prfd	15	98.00	60.00	158.00	104.8667	35.47004	1258.124
KF_AG_EMG	15	7.46	3.82	11.28	7.6343	2.63672	6.952
KF_time_PkAG_EMG_Pk	15	2180.00	9.00	2189.00	488.2667	709.76238	503762.638
KF_amp_AG_EMG_Prfd	15	9.28	1.54	10.82	4.9062	2.73224	7.465
KF_Q30	14	33.33	1.76	35.09	12.9365	10.56188	111.553
KF_Q30_EMG_Pk	14	4.06	.46	4.52	1.7233	1.38600	1.921
KF_QpkAG	15	237.97	59.90	297.88	156.1362	72.64514	5277.317
KF_QpkAG_EMG_Pk	15	15.23	11.17	26.41	19.8226	4.02982	16.239

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
KF_AG_EMD	15	81.00	35.00	116.00	76.5333	22.59541	510.552
KF_AG_EMG_On_pkRFD_dela	15	142.00	128.00	270.00	181.4000	45.36015	2057.543
KF_PkAN_EMG	15	1.33	.19	1.52	.4239	.33340	.111
KF_time_PkAN_EMG	15	2278.00	-9.00	2269.00	788.9333	833.93854	695453.495
KF_AmpAN_EMGPkRFD	15	.29	.05	.34	.1875	.06653	.004
KF_Q30AN	15	3.12	.35	3.47	1.4388	1.00718	1.014
KF_QpkAN_EMG	15	7.15	2.00	9.16	5.5853	1.78066	3.171
KF_AN_EMD	15	137.00	10.00	147.00	67.6667	46.56434	2168.238
KF_AN_EMD_On_PkRFD_dela	15	201.00	81.00	282.00	170.6667	67.75340	4590.524
KF_Mmax_Frc	15	69.58	73.07	142.65	101.0589	21.95350	481.956
KF_Mmax_EMGag	15	4.99	2.16	7.14	4.3597	1.60923	2.590
KF_Mmax_EMGan	15	.11	.11	.23	.1710	.03066	.001
KF_Cocontraction	15	.05	.02	.08	.0439	.01665	.000
KF_Coactivation	15	.07	.02	.08	.0412	.01887	.000

Appendix N: Elbow flexion contraction characteristics of the endurance-trained and untrained boys and men

	Children		Adults		Effect
	Control	Endurance	Control	Endurance	
Torque: Absolute	$18.3 \pm 4.4^{a,c}$	$25.6 \pm 7.9^{b,c}$	$71.4 \pm 8.9^{a,d}$	$66.9 \pm 7.5^{b,d}$	A, A*T
Per Kg	0.5 ± 0.1^{a}	0.6 ± 0.1^{b}	0.9 ± 0.2^{a}	0.9 ± 0.1^{b}	A
Per CSA_a	0.6 ± 0.1^{a}	0.7 ± 0.1^{b}	1.1 ± 0.2^{a}	1.0 ± 0.1^{b}	A, A*T(0.080)
Per LBM	$0.6 \pm 0.1^{a,c}$	$0.8 \pm 0.2^{b,c}$	1.1 ± 0.2^{a}	1.1 ± 0.1^{b}	A, A*T
Per CSA_u	0.07 ± 0.02^{a}	0.06 ± 0.02^{b}	0.09 ± 0.03^{a}	0.1 ± 0.05^{b}	A
RFD: Absolute	$99.1 \pm 43.8^{a,c}$	$152.5 \pm 66.2^{b,c}$	$567.4 \pm 138.8^{a,d}$	$505.4 \pm 138.7^{b,d}$	A, A*T
Per torque	5.1 ± 1.7^{a}	5.8 ± 1.4^{b}	8.0 ± 2.0^{a}	7.5 ± 1.8^{b}	A
Q_{30}: Absolute	1.6 ± 1.3^{a}	1.9 ± 1.3^{b}	6.0 ± 8.2^{a}	6.8 ± 4.0^{b}	A
Per EMG_{amp}	1.0 ± 0.6^{a}	0.9 ± 0.5^{b}	1.5 ± 1.3^{a}	2.2 ± 1.2^{b}	A
Q_{pk}: Abolute	21.0 ± 12.3^{a}	23.9 ± 11.3^{b}	55.3 ± 41.5^{a}	52.4 ± 20.6^{b}	A
Per EMG_{amp}	11.7 ± 3.3^{a}	12.1 ± 2.7^{b}	15.8 ± 5.1^{a}	15.9 ± 3.7^{b}	A
EMD	77.0 ± 23.7^{a}	67.3 ± 19.9^{b}	53.6 ± 10.6^{a}	47.8 ± 15.2^{b}	A, T(0.097)
T to peak torque	1556.4 ± 743.8	1474.2 ± 439.3	1215.9 ± 667.8	1171.8 ± 762.4	A(0.071)
T to peak RFD	$93.6 \pm 21.2^{a,c}$	$79.3 \pm 11.1^{b,c}$	69.0 ± 12.2^{a}	70.8 ± 10.7^{b}	A, A*T
Co-activation	0.8 ± 0.46	0.6 ± 0.4	0.6 ± 0.5^{a}	0.4 ± 0.2^{a}	T
Co-contraction	0.4 ± 0.2^{a}	0.3 ± 0.2^{b}	0.1 ± 0.07^{a}	0.1 ± 0.06^{b}	A

Values are presented as $M \pm SD$. Similar superscripts indicate pairwise significant differences ($p < 0.05$).
A = Age effect, T = Training effect, A*T = Age and training interaction ($p < 0.05$)

Appendix O: Elbow extension contraction characteristics for endurance-trained and untrained boys and men

	Children		Adults		Effect
	Control	Endurance	Control	Endurance	
Torque: Absolute	21.5 ± 5.9^{a}	28.6 ± 13.8^{b}	59.1 ± 6.8^{a}	58.5 ± 12.1^{b}	A
Per Kg	0.6 ± 0.2^{a}	0.7 ± 0.2^{b}	0.7 ± 0.1^{a}	0.8 ± 0.2^{b}	A
Per CSA_a	0.8 ± 0.1^{a}	0.8 ± 0.2^{b}	0.9 ± 0.2^{a}	0.9 ± 0.2^{b}	A
Per LBM	0.8 ± 0.2^{a}	0.9 ± 0.3	0.9 ± 0.1^{a}	0.9 ± 0.2	A
Per CSA_u	0.08 ± 0.02	0.07 ± 0.02	0.08 ± 0.02^{a}	0.06 ± 0.02^{a}	T
RFD: Absolute	$105.1 \pm 43.3^{a,c}$	$155.2 \pm 81.1^{b,c}$	$518.5 \pm 113.3^{a,d}$	$466.5 \pm 107.1^{b,d}$	A, A*T
Per torque	4.8 ± 1.5^{a}	5.4 ± 1.6^{b}	8.9 ± 1.9^{a}	8.2 ± 2.1^{b}	A
Q_{30}: Absolute	0.8 ± 0.6	0.9 ± 1.1	0.7 ± 0.7^{a}	1.5 ± 1.3^{a}	T
Per EMG_{amp}	1.2 ± 0.8	0.9 ± 0.7	0.9 ± 0.9^{a}	1.4 ± 0.8^{a}	A*T(0.075)
Q_{pk}: Abolute	9.6 ± 5.1	13.4 ± 11.3	14.04 ± 16.4	18.1 ± 9.5	
Per EMG_{amp}	12.9 ± 4.4	12.8 ± 4.3^{a}	14.6 ± 4.8	16.9 ± 3.3^{a}	A
EMD	67.8 ± 29.2	68.3 ± 30.4^{b}	60.2 ± 22.8	46.7 ± 18.8^{a}	A
T to peak torque	1867.1 ± 489.0	1714.7 ± 549.6^{a}	1794.8 ± 761.5^{b}	$943.1 \pm 534.7^{a,b}$	A, T, A*T
T to peak RFD	83.2 ± 19.9^{a}	85.3 ± 21.5^{b}	63.1 ± 8.2^{a}	68.8 ± 10.3^{b}	A
Co-activation	0.1 ± 0.08^{a}	0.09 ± 0.05^{b}	0.04 ± 0.03^{a}	0.03 ± 0.04^{b}	A
Co-contraction	$0.3 \pm 0.1^{a,c}$	$0.2 \pm 0.1^{b,c}$	$0.2 \pm 0.07^{a,d}$	$0.10 \pm 0.07^{b,d}$	A, T

Values are presented as M ± SD. Similar superscripts indicate pairwise significant differences ($p < 0.05$).
A = Age effect, T = Training effect, A*T = Age and training interaction ($p < 0.05$).

Appendix P: Knee extension contraction characteristics for endurance-trained and untrained boys and men

	Children		Adults		Effect
	Control	Endurance	Control	Endurance	
Torque: Absolute	$71.8 \pm 23.9^{a,c}$	$96.9 \pm 32.5^{b,c}$	226.2 ± 42.5^{a}	211.4 ± 39.5^{b}	A, A*T
Per Kg	2.1 ± 0.5^{a}	2.4 ± 0.6^{b}	2.8 ± 0.5^{a}	2.8 ± 0.4^{b}	A
Per CSA_t	4.7 ± 1.9	5.1 ± 1.1	5.9 ± 2.2	5.1 ± 0.7	
Per LBM	$2.5 \pm 0.7^{a,c}$	$3.0 \pm 0.6^{b,c}$	3.5 ± 0.6^{a}	3.3 ± 0.5^{b}	A, A*T(0.054)
Per CSA_u	0.12 ± 0.04^{a}	0.14 ± 0.05	$0.18 \pm 0.06^{a,b}$	0.15 ± 0.04^{b}	A, A*T(0.053)
RFD: Absolute	352.9 ± 155.1^{a}	468.0 ± 185.3^{b}	1343.4 ± 364.3^{a}	1228.7 ± 358.9^{b}	A
Per torque	5.0 ± 1.5^{a}	4.7 ± 1.2^{b}	6.0 ± 1.3^{a}	5.8 ± 1.2^{b}	A
Q_{30}: Absolute	0.4 ± 0.2^{a}	0.6 ± 0.4^{b}	$0.7 \pm 0.6^{a,c}$	$1.5 \pm 0.9^{b,c}$	A, T, A*T
Per EMG_{amp}	0.9 ± 0.5	1.1 ± 0.6^{a}	1.1 ± 0.7^{b}	$1.9 \pm 1.2^{a,b}$	A, T, A*T(0.065)
Q_{pk}: Abolute	7.9 ± 3.5	8.8 ± 4.2^{a}	10.1 ± 6.3	13.2 ± 6.0^{a}	A
Per EMG_{amp}	16.3 ± 4.4	15.9 ± 3.0	15.6 ± 4.3	16.6 ± 3.7	
EMD	68.0 ± 17.5	59.9 ± 19.6	58.9 ± 15.5	53.6 ± 15.1	A (0.077)
T to peak torque	1403.4 ± 572.5	1596.9 ± 631.1	1266.6 ± 610.0	1231.2 ± 555.1	A (0.099)
T to peak RFD	94.5 ± 22.2^{a}	104.6 ± 41.1^{b}	79.3 ± 11.9^{a}	81.9 ± 18.5^{b}	A
Co-activation	0.1 ± 0.1	0.1 ± 0.2	0.1 ± 0.06	0.1 ± 0.07	
Co-contraction	0.2 ± 0.08	0.2 ± 0.2	0.1 ± 0.07	0.1 ± 0.08	A(0.057)

Values are presented as $M \pm SD$. Similar superscripts indicate pairwise significant differences ($p < 0.05$).
A = Age effect, T = Training effect, A*T = Age and training interaction.

Appendix Q: Knee flexion contraction characteristics for endurance-trained and untrained boys and men

	Children		Adults		Effect
	Control	Endurance	Control	Endurance	
Torque: Absolute	35.3 ± 12.3[a]	47.5 ± 16.7[b]	101.5 ± 20.3[a]	101.8 ± 21.5[b]	A
Per Kg	1.0 ± 0.2[a]	1.2 ± 0.3[b]	1.3 ± 0.3[a]	1.4 ± 0.3[b]	A, T(0.071)
Per CSA_t	2.2 ± 0.7	2.5 ± 0.6	2.8 ± 0.7	2.5 ± 0.6	A(0.077), A*T(0.080)
Per LBM	1.2 ± 0.3[a]	1.5 ± 0.3	1.5 ± 0.3[a]	1.6 ± 0.3	A, T(0.076)
Per CSA_u	0.03 ± 0.009[a]	0.04 ± 0.03	0.05 ± 0.02[a]	0.05 ± 0.02	A
RFD: Absolute	184.1 ± 57.6[a]	237.8 ± 86.5[b]	621.6 ± 150.3[a]	636.0 ± 227.8[b]	A
Per torque	5.3 ± 1.0[a]	5.0 ± 0.9[b]	6.2 ± 1.5[a]	6.1 ± 1.2[b]	A
Q_{30}: Absolute	0.6 ± 0.5[a]	0.6 ± 0.3[b]	0.7 ± 0.6[a]	1.3 ± 1.1[b]	A
Per EMG_{amp}	1.1 ± 0.9[a]	1.1 ± 0.6[b]	1.5 ± 0.8[a]	1.7 ± 1.4	A(0.058)
Q_{pk}: Absolute	10.2 ± 6.2	10.9 ± 4.9	10.7 ± 6.1	15.6 ± 7.3	T(0.084)
Per EMG_{amp}	16.4 ± 3.8[a]	17.8 ± 2.0[b]	20.6 ± 3.5[a]	19.8 ± 4.0[b]	A
EMD	88.4 ± 27.8[a]	87.8 ± 18.0[b]	73.6 ± 23.9[a]	76.5 ± 22.6[b]	A
T to peak torque	1459.4 ± 563.2	1458.8 ± 566.3[a]	1362.9 ± 696.1[b]	733.8 ± 266.3[a,b]	A, T, A*T
T to peak RFD	109.4 ± 27.2	116.8 ± 41.8	97.8 ± 42.2	104.8 ± 35.5	
Co-activation	0.08 ± 0.03[a]	0.09 ± 0.06[b]	0.05 ± 0.02[a]	0.04 ± 0.02[b]	A
Co-contraction	0.09 ± 0.1	0.08 ± 0.04	0.07 ± 0.06	0.04 ± 0.02	

Values are presented as M ± SD. Similar superscripts indicate pairwise significant differences ($p < 0.05$).
A = Age effect, T = Training effect, A*T = Age and training interaction ($p < 0.05$).

Appendix R: Summary of ANOVA significant statistical effects - Elbow Flexion

	Age effect	Training effect	Age*Training interaction
Torque: Absolute	**<0.001**		**0.003**
Per Kg	**<0.001**		
Per CSA_a	**<0.001**		**0.080**
Per LBM	**<0.001**		**0.010**
Per CSA_u	**<0.001**		
RFD: Absolute	**<0.001**		**0.043**
Per torque	**<0.001**		
Q_{30}: Absolute	**<0.001**		
Per EMG_{amp}	**<0.001**		
Q_{pk}: Abolute	**<0.001**		
Per EMG_{amp}	**<0.001**		
EMD	**<0.001**	0.097	
T to peak torque	0.071		
T to peak RFD	**<0.001**		**0.039**
Co-activation		**0.045**	
Co-contraction	**<0.001**		

Values are P values. Significant values are in bold $P<0.05$.

Appendix S: Summary of ANOVA significant statistical effects - Elbow Extension

		Age effect	Training effect	Age*Training interaction
Torque:	Absolute	**<0.001**		
	Per Kg	**0.007**		
	Per CSA_a	**0.045**		
	Per LBM	**0.039**		
	Per CSA_u		**0.038**	
RFD:	Absolute	**<0.001**		**0.034**
	Per torque	**<0.001**		
Q_{30}:	Absolute		**0.038**	
	Per EMG_{amp}			0.075
Q_{pk}:	Abolute			
	Per EMG_{amp}	**0.010**		
EMD		**0.029**		
T to peak torque		**0.009**	**0.002**	**0.028**
T to peak RFD		**<0.001**		
Co-activation		**<0.001**		
Co-contraction		**<0.001**	**0.028**	

Values are P values. Significant values are in bold $P<0.05$.

Appendix T: Summary of ANOVA significant statistical effects - Knee Extension

		Age effect	Training effect	Age*Training interaction
Torque:	Absolute	**<0.001**		**0.031**
	Per Kg	**<0.001**		
	Per CSA_t			
	Per LBM	**<0.001**		0.054
	Per CSA_u	**0.005**		0.053
RFD:	Absolute	**<0.001**		
	Per torque	**0.004**		
Q_{30}:	Absolute	**<0.001**	**0.002**	**0.034**
	Per EMG_{amp}	**0.010**	**0.015**	0.065
Q_{pk}:	Abolute	**0.018**		
	Per EMG_{amp}			
EMD		0.077		
T to peak torque		0.099		
T to peak RFD		**0.003**		
Co-activation				
Co-contraction		0.057		

Values are P values. Significant values are in bold $P<0.05$

Appendix U: Summary of ANOVA significant statistical effects - Knee Flexion

		Age effect	Training effect	Age*Training interaction
Torque:	Absolute	**<0.001**		
	Per Kg	**0.001**	0.071	
	Per CSA_t	0.077		0.080
	Per LBM	**0.004**	0.076	
	Per CSA_u	**0.009**		
RFD:	Absolute	**<0.001**		
	Per torque	**0.002**		
Q_{30}:	Absolute	**0.021**		
	Per EMG_{amp}	0.058		
Q_{pk}:	Absolute		0.084	
	Per EMG_{amp}	**0.001**		
EMD		**0.035**		
T to peak torque		**0.005**	**0.030**	**0.030**
T to peak RFD				
Co-activation		**<0.001**		
Co-contraction				

Values are P values. Significant values are in bold $P<0.05$

Appendix V: ANOVA results: main effects and interactions for all four contractions

		Elbow flexion	Elbow extension	Knee extension	Knee flexion
Torque:	Absolute	A,A*T	A	A,A*T	A
	Per Kg	A	A	A	A,T(0.071)
	Per CSA_t	A,A*T(0.080)	A		A(0.077),A*T(0.080)
	Per LBM	A,A*T	A	A,A*T(0.054)	A,T(0.076)
	Per CSA_u	A	T	A,A*T(0.053)	A
RFD:	Absolute	A,A*T	A,A*T	A	A
	Per torque	A	A	A	A
Q_{30}:	Absolute	A	T	A,T,A*T	A
	Per EMG_{amp}	A	A*T(0.075)	A,T,A*T(0.065)	A(0.058)
Q_{pk}:	Absolute	A		A	T(0.084)
	Per EMG_{amp}	A	A		A
EMD		A,T(0.097)	A	A(0.077)	A
T to peak torque		A(0.071)	A,T,A*T	A(0.099)	A,T,A*T
T to peak RFD		A,A*T	A	A	
Co-activation		T	A		A
Co-contraction		A	A,T	A(0.057)	

A = Age effect, T = Training effect, A*T = Age and training interaction ($p < 0.05$).

Appendix W: Bivariate Correlations – Elbow flexion

	Whole group	Men	Boys
Peak torque/Peak EMG_{amp}	0.55**	-	-
Q_{30} per peak EMG_{amp}/EMD	-0.53**	-0.43*	-0.45*
Peak RTD/Q_{30}	0.54**	-0.40*	-
Peak $RTD_{per\ torque}$/ Q_{30} per peak EMG_{amp}	0.53**	0.42*	0.46*

* P<0.05, ** P<0.01

Appendix X: Bivariate Correlations – Elbow extension

	Whole group	Men	Boys
Peak torque/Peak EMG_{amp}	-	-	-
Q_{30} per peak EMG_{amp}/EMD	-0.49**	-0.56**	-0.40*
Peak RTD/Q_{30}	-	-	-
Peak $RTD_{per\ torque}$/ Q_{30} per peak EMG_{amp}	-	-	0.55**

* P<0.05, ** P<0.01

Appendix Y: Bivariate Correlations – Knee extension

	Whole group	Men	Boys
Peak torque and Peak EMG_{amp}	0.33**	-	-
Peak RTD and Q_{30}	0.41**	-	-
Peak $RTD_{per\ torque}$ and Q_{30} per peak EMG_{amp}	0.36**	0.45**	-
Q_{30} per peak EMG_{amp} and EMD	-0.53**	-0.58**	-

* P<0.05, ** P<0.01

Appendix Z: Bivariate Correlations – Knee flexion

	Whole group	Men	Boys
Peak torque/Peak EMG_{amp}	-	-	-
Q_{30} per peak EMG_{amp}/EMD	-0.51**	-0.40*	-
Peak RTD/Q_{30}	0.30*	-	-
Peak $RTD_{per\ torque}$/ Q_{30} per peak EMG_{amp}	0.29*	0.35*	-

* P<0.05, ** P<0.01

Appendix AA: ANOVA for repeated measures including all four types of contractions

		Age effect	Training effect	Age*Training interaction
Torque:	Absolute	**<0.001**	-	**0.018**
	Per Kg	**<0.001**	-	-
	Per CSA	**0.007**	-	**0.038**
	Per LBM	**<0.001**	0.097	**0.024**
	Per CSA_u	**0.001**	-	-
RFD:	Absolute	**<0.001**	-	0.085
	Per torque	**<0.001**	-	-
Q_{30}:	Absolute	**<0.001**	-	-
	Per EMG_{amp}	**<0.001**	0.060	**0.025**
Q_{pk}:	Absolute	**<0.001**	-	-
	Per EMG_{amp}	**<0.001**	-	-
EMD		**<0.001**	-	-
T to peak torque		**0.001**	-	0.093
T to peak RFD		**<0.001**	-	-
Co-activation		**0.010**	**0.025**	-
Co-contraction		**<0.001**	0.064	-

Values are P values. Significant values are in bold $P<0.05$