Do Neuro-Muscular Adaptations Occur in Endurance-Trained Boys and Men?

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Running title: Effect of age and endurance training on muscle function

Abstract

Most research on the effects of endurance training has focused on its health-related benefits and metabolic effects in both children and adults. The purpose of this study was to examine neuromuscular effects of endurance training and whether they differ in children (9.0-12.9 yrs) compared with adults (18.4-35.6 yrs). Maximal isometric torque, rate of torque development (RTD), rate of muscle activation (Q_{30}), electro-mechanical delay (EMD), and time to peak torque and peak RTD were determined by isokinetic dynamometry and surface electromyography, in elbow and knee flexion and extension. Subjects were 12 endurance-trained and 16 untrained boys, and 15 endurance-trained and 20 untrained men. Adults displayed consistently higher peak torque, RTD, and Q_{30}, in both absolute and normalized values, while boys had longer EMD (64.7±17.1 vs. 56.6±15.4 ms) and time to peak RTD (98.5±32.1 vs. 80.4±15.0 ms for boys and men, respectively). $Q_{30,}$ normalized for peak EMG amplitude, was the only observed training effect (1.95±1.16 vs. 1.10±0.67 ms for trained and untrained men, respectively). This effect could not be shown in the boys. The findings show normalized muscle strength and rate of activation to be lower in children compared with adults, regardless of training status. As observed higher Q_{30} values were not matched by corresponding higher performance measures in the trained men, the functional and discriminatory significance of Q_{30} remains unclear. Endurance training does not appear to affect muscle strength or rate of force development in either men or boys.

Key words: Children, EMG, Exercise, Strength, Swimming, Training

INTRODUCTION

Previous research on the effects of endurance-type training has focused mainly on health-related benefits and physiological adaptations related to aerobic capacity. The focus on cardiovascular health and metabolic adaptations to endurance training is evident in the adult (1998; Pang et al. 2006), as well as in the pediatric literature (Armstrong et al. 2007; Janz et al. 2002). Corresponding research on neuromuscular adaptations to endurance-type training is notably lacking.

Resistance training has been shown to enhance muscle strength in both children and adults. In adults, both morphological and neurological adaptations explain the increase in strength (Aagaard 2003; Aagaard et al. 2002). In children, recent studies demonstrate that increased general physical activity (12 months to 6 years) results in enhanced total lean body mass (Baxter-Jones et al. 2008; Stenevi-Lundgren et al. 2009). However, resistance training (up to 20 weeks) has not been shown to result in muscle hypertrophy. Thus, it is presumed that strength is enhanced through neuromuscular adaptations (Behm et al. 2008; Ozmun et al. 1994; Ramsay et al. 1990; Sale 1988). Comparable data on the possible effects of endurance training on muscle performance and neuromuscular adaptations are limited. While some studies suggest increased muscle activation and possibly increased strength in adult endurance athletes compared with untrained adults (Lattier et al. 2003; Lucia et al. 2000), there are no comparable data in children.

It has been suggested that the capacity of pre-pubertal boys to activate their neuromuscular system is lower than that of adults (Belanger and McComas 1989; Grosset et al. 2008; Hatzikotoulas et al. 2008; O'Brien et al. 2009; Paasuke et al. 2000), and that children are less capable of recruiting or utilizing their higher-threshold motor units (Asai and Aoki 1996; Falk and Dotan 2006; Falk et al. 2009b). While not all studies have demonstrated a lower motor unit activation in children (Streckis et al. 2007), Halin et al. (Halin et al. 2002) proposed that children's neuromuscular system may be more adaptive to a training stimulus compared with adults.

The present study examined whether endurance training results in neuromuscular adaptations. Furthermore, since children appear to differ neuro-muscularly from adults, a secondary purpose of this study is to differentiate the age-related training effects, if any.

METHODS

The study and its procedures were approved by the Brock University Research Ethics Board (file #05-155). Sixty-three participants volunteered to take part in the study: 16 untrained boys (9-12 yrs), 20 untrained men (18-25 yrs), 12 endurance-trained boys (9-11 yrs), and 15 endurance-trained men (18-35 yrs). The untrained participants were involved in structured physical activity for a maximum of 2 hours per week. 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 boys had been training for 2.5+0.9 yrs, and the men for 6.4 + 4.3 yrs. The adult athletes specialized in middle and long distances events (200-1500m). No such specialization existed in the boys. Six endurance-trained men participated in their sport at a National level, three men competed at a regional level and the rest were university-aged varsity swimmers. Seven boys competed at a provincial level, while five boys participated at regional level.

All the boys were classified as pre-and early-pubertal based, on secondary sexual characteristics (pubic hair), as described by Tanner (Tanner 1962).

Those subjects who had prior or present conditions 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.

Procedures: All tests and measurements were performed during two visits to the laboratory. Subjects were instructed to refrain from excessive 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. Subsequently, anthropometric measurements (mass, height, sitting height and skinfold thickness) 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. These data were not used for analysis. 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 along with electromyography signal (EMG) acquisition.

Anthropometric measurements: 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. 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 (Durnin and Womersley 1974; Slaughter 1988). All measurements were performed by the same investigator. The coefficient of variance (CV) was 5% and the intra-observer reliability (ICC) in 10 subjects was $r = 0.98$.

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

Questionnaires: Questionnaires were completed by the subject, if needed with the help of the investigator and possibly parent, to assess the subject's medical history, physical activity levels and training history for the athletes. Physical activity level was assessed using a standardized questionnaire (Godin and Shephard 1985), as well as by a personal interview. Past and present training experience was self-reported, through a personal interview.

Strength Testing Protocol: An isokinetic dynamometer system (Biodex III, Biodex, Shirley, NY) was used to assess isometric strength (torque) of the elbow and knee flexors and extensors of the dominant arm and leg, respectively. Isometric contractions were chosen to minimize antagonist involvement so as to make torque measurements attributable to agonist action as much as possible. The isokinetic dynamometer system was found reliable for measuring muscle strength in children and adults (Dvir 2004). The intra-session reliability for maximal strength reliability coefficient ($ICC_{2,1}$) was 0.95 and 0.93 for boys and men, respectively. A similar protocol was used in previous studies in the pediatric and adult population in our laboratory

(Falk et al. 2009a; Falk et al. 2009b). 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 a specific warm-up (~5 contractions of progressive intensity), followed by two sets of five 3-seconds maximal voluntary contractions (MVC). 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. Additional repetitions were performed as needed, to reach at least 5 valid trials. Data were deemed unacceptable due to execution errors, deviations in EMG baseline, or abnormal torque or EMG amplitudes. Each subject was instructed to contract "as hard and as fast as possible" from a relaxed state to ensure maximal torque and rate of torque development (RTD). Subjects were verbally encouraged to perform a maximal effort throughout each contraction. Online visual feedback of the dynamometer's torque signal was available for the subjects on a PC screen. Visual feedback has been shown to be important for torque production (Kellis and Baltzopoulos 1996), especially in young children (Smits-Engelsman et al. 2003). Peak torque was recorded from the dynamometer system and stored for off-line analysis.

Electromyography (EMG): During each contraction, 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 and 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.

The EMG signal was 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.

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. Inclusion for analysis was based on clear and stable EMG baseline prior to the beginning of the contraction and clear onset of torque and EMG activity. Any faulty trials were eliminated and out of the remaining trials, the best five repetitions were used for analysis, based on the highest peak torques and RTD values. The intra-session reliability for agonist EMG amplitude reliability coefficient ($ICC_{2,1}$) was 0.65 and 0.94 for boys and men, respectively.

Traces were time-locked on the torque onset and averaged. The average waveform consisted of 400 ms prior to the force onset and 3000 ms afterwards. The mean traces were used to calculate peak torque, RTD, rate of rise of muscle activation (Q_{30}), electro-mechanical delay (EMD), time to peak torque, time to peak RTD, and agonist-antagonist 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 EMG amplitudes were calculated from the detected linear envelope. The peak EMG amplitudes values were calculated over 250ms around the time of occurrence of peak torque. Q_{30} was measured over the first 30ms of electromechanical activity. Q_{30} was defined as the area under the linear envelope of the detected EMG signal during the initial 30 ms (Gabriel and Boucher 2000; Gottlieb et al. 1989), and has been previously used to reflect rate of increase in muscle activation during a maximal task (Falk et al. 2009a; Falk et al. 2009b; Gabriel and Boucher 2000; Gottlieb et al. 1989). The EMG activity onset was defined as the point in time at which the signal first increased 5 standard deviations above the mean of the baseline and stayed above that point for more than 20 msec. The onset of torque was defined as the first point in time where the RTD reached 5 standard deviations of the baseline mean for at least 10 ms. This point was confirmed visually and adjusted manually if needed. EMD was defined as the delay, in ms, between the agonist EMG activity onset and the onset of torque production. 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].

Statistical Analysis: All statistical analyses were performed using SPSS v.16 (SPSS Inc., Chicago, IL). The data for all groups are presented as mean (M) ±1 standard deviation (SD). The data were cleaned by checking for outliers (>2 standard deviations from the mean) of all dependent variables for each of the four contractions. In total, four outlying values were found (one value of Q_{30} in each of the four contraction modes) and were not included in the analysis. 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 and age as the between-subjects main effects. *Post hoc* comparisons (LSD) were performed when a main effect or interaction was found to be statistically significant. 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 $p < 0.05$.

RESULTS

The physical characteristics of the subjects are displayed in table 4.1. The men were older, taller, and heavier, with greater lean body mass than the children. There was no significant difference in age or height 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 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. There were no significant differences between and within the age groups in relative body fat. There were no significant differences in sexual maturation stage and years from age of peak height velocity between the two boys groups (Table 1).

[Table 1]

There was a significant difference in training hours between groups. The adults trained 14.4±5.0 hr/wk while the boys trained 8.5±3.6 hr/wk. Both the men and the boys participated in dry-land training which included limited resistance exercise in addition to their endurance-training program (2.5±1.3 hr/wk and 3.4±1.5 hr/wk, respectively).

Data for all four contraction modes (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. The results of all contraction modes are summarized in Table 2 (see below).

In absolute terms, men were significantly stronger than boys (Figure 1a). There was an age-by-training interaction, reflecting the fact that the trained boys were significantly stronger than the untrained boys, while no such difference was apparent in the adults. When peak torque was normalized to body mass (Figure 1b), an age effect was still apparent, reflecting the fact that on average, normalized torque was higher in the men. However, differences between trained and untrained boys were no longer significant.

[Figure 1a,b]

Men exhibited a more rapid absolute RTD than boys during knee extension (Figure 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 (Figure 2b). No age-by-training interactions were apparent either in absolute terms or when RTD was normalized to peak torque.

[Figure 2a,b]

Men had significantly higher absolute Q_{30} compared with boys (Figure 3a). There was a training effect, reflecting the fact that on average, the athletes had higher Q_{30} compared with the non-athletic groups. More importantly, there was an age-by-training interaction, which reflects the fact that the trained men had significantly higher Q_{30} compared with their age-matched untrained group, while the difference between the trained and untrained boys was not significant.

When Q_{30} was normalized to peak EMG amplitude (Figure 3b), age and training effects were still significant. There was also a trend toward age by training interaction (p=0.090), reflecting the fact that the endurance-trained men had 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 3a,b]

There were no significant differences in time to peak torque between the two age and training groups (Figure 4a). However, the time to peak RTD was significantly longer in the boys compared with the men (figure 4b). No training effect or training-by-age interaction were evident.

[Figure 4a,b]

Men had significantly shorter EMD compared with boys (Figure 5). No training effect or age-by-training interactions were detected.

[Figure 5]

The co-activation index was low in all groups and similar in the trained and untrained boys (0.15±0.17 and 0.11±0.05, respectively), as well as in the trained and untrained men (0.09±0.07 and 0.13±0.06, respectively). No age effect or age-by-training interactions were found.

Repeated measures analysis: Table 2 presents the results of the ANOVA for repeated measures analysis highlighting only the significant effects. 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 modes 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 values. Furthermore, EMD, time to peak RTD and peak torque were significantly longer in boys compared with men. The co-activation index was lower in men compared with boys. In addition, the training effect was apparent only in co-activation index, which reflects the fact that on average the athletes had lower co-activation index than the untrained subjects. However, it should be noted that generally, co-activation indices were very low (<0.20) in all groups.

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 controls. This was not the case in the men. When peak torque was normalized for body mass, no training effect or interactions were observed. 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 such difference was apparent between the two boys groups.

[Table 2]

DISCUSSION

We compared maximal isometric torque, rate of torque development, and rate of muscle activation of elbow and knee flexion and extension, in endurance-trained and minimally-active boys and 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 body mass, peak torque or peak EMG amplitude, respectively. No training-related muscle-performance differences were observed but trained men had significantly higher Q_{30} compared with the untrained men. While Q_{30} also tended to be higher in the trained boys, the difference was not statistically significant.

The lower peak torque observed in the boys is in agreement with previous studies of untrained children and adults (De Ste Croix et al. 1999; Lambertz et al. 2003). Our study extends previous results by demonstrating that this age-related difference also exists among endurance-trained athletes.

Overall, children's co-activation index was found to be similar or slightly higher than that of adults. However, in both age groups and in all contraction modes, co-activation was very low and could not explain the higher size-normalized peak torque observed in our adult subjects. This is in agreement with previous studies which examined isometric strength of untrained boys and men (Falk et al. 2009b; Morse et al. 2008; O'Brien et al. 2009), although not with all (Hatzikotoulas et al. 2008).

Age-related differences in muscle fibre-type distribution could potentially explain differences in normalized peak torque. However, previous studies have demonstrated no age difference in fibre-type distribution between children and adults (Dubowitz 1965). Thus, the boys' lower peak torque should, at least in part, be explained by their lower rate of muscle activation, as reflected by the lower Q_{30} observed in the present study, and by a lower extent of motor unit recruitment, as suggested previously (Belanger and McComas 1989; Falk et al. 2009b; Halin et al. 2003; Paasuke et al. 2000).

No difference was observed in peak torque between the trained and untrained men in either absolute or body-mass normalized terms. This is consistent with previous findings (Sleivert et al. 1995), suggesting that endurance training has little or no effect on maximal strength.

In absolute terms, peak torque was significantly higher in the trained boys than in their age-matched counterparts. This was mainly due to the trained-boys' greater body mass. Indeed, normalized to body mass, the peak torque difference was statistically insignificant. Two previous studies reported greater maximal isometric knee extensor strength in young male gymnasts (power-trained) compared with swimmers (endurance-trained). However, no comparison was made with untrained boys (Bencke et al. 2002; Maffulli et al. 1994). While previous findings have demonstrated that increased general physical activity in girls (Stenevi-Lundgren et al. 2009) or cycle ergometry training in boys (Zakas 2004) can result in increased muscle strength, our findings suggest that young endurance athletes do not demonstrate clear strength advantage over their untrained counterparts.

The boys' lower absolute RTD is partly explained by its dependency on peak torque. Thus, normalizing RTD for peak torque can be useful in searching for more fundamental RTD-determining factors (Holtermann et al. 2007). The only two studies to have normalized children's RTD to peak torque, similarly reported lower RTD values in boys during elbow flexion and extension compared with men (Asai and Aoki 1996; Falk et al. 2009b). Children's lower RTD then is a persistent finding, independent of their lower maximal strength or tested muscle group. These results suggest that other factors, such as lower rate of muscle activation or firing rate (Van Cutsem et al. 1998), are likely involved in determining children's RTD.

Peak RTD was higher in the men than in the boys, but no training effect was evident in either age group. RTD has previously been shown to rise following heavy resistance training (Aagaard et al. 2002), and to be higher in athletes primarily involved in explosive type of training (Sleivert et al. 1995). However, no comparable difference was observed in endurance-trained athletes (Sleivert et al. 1995). Additionally, Lattier et al. (Lattier et al. 2003) found no differences in the mean rate of twitch force development of the knee extensors between endurance-trained and sedentary men.

Shorter EMD reflects greater muscle-tendon stiffness, excitation-contraction coupling, and muscle-fibre conduction velocity (Cavanagh and Komi 1979; Halin et al. 2003). Compared with the men, our boys had longer EMD. Comparable age-related EMD difference has been reported earlier in elbow flexion (Asai and Aoki 1996; Falk et al. 2009b), elbow extension (Falk et al. 2009b), and plantar-flexion twitch contraction (Grosset et al. 2005). While no age-related differences in muscle-tendon stiffness was reported in elbow flexion (Cornu and Goubel 2001), others reported lower stiffness in boys during dorsiflexion (Lambertz et al. 2003). Thus, the boys' longer EMD may be attributed to their lower musculo-tendinous stiffness (Lambertz et al. 2003) and to lower muscle activation or muscle fibre conduction velocity in boys (Halin et al. 2003).

Grosset et al. (Grosset et al. 2009) found EMD to be significantly shorter after ten weeks of endurance training in men. While the EMD difference in the present study was not significant, there was a trend for shorter EMD in the trained subjects (p=0.069). Tendon stiffness was previously reported to increase after endurance training (Buchanan and 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 dependent on the muscle-tendon stiffness (Cavanagh and Komi 1979), Grosset et al. (Grosset et al. 2009) found musculo-tendinous stiffness changes to account for only 20% of the variance in training-induced EMD changes. Thus, the rate of muscle activation and the type of recruited MUs could not be ruled out as likely contributors to EMD and changes thereof.

As previously reported (Falk et al. 2009b), our boys had lower normalized Q_{30} values compared with men. Also, our trained men were characterized by significantly greater Q_{30} values than their untrained counterparts. While the pattern was similar in the boys, the difference did not reach statistical significance. To the best of our knowledge this is the first study to examine Q_{30} in endurance-trained boys and men. Our results concur with previous studies on adults (Lattier et al. 2003; Lucia et al. 2000), that suggested endurance training increases muscle activation and enhances motor-unit recruitment. However, we feel that since our findings could not correlate performance with Q_{30} differences, the relationship between Q_{30} and muscle performance is unclear, at least as far as endurance training is concerned. Lucia et al. (Lucia et al. 2000) suggested that the increased motor-unit activation in endurance athletes was primarily of type-I fibres. This suggestion does not help in clarifying the issue since increased activation, even if only of type-I motor units, should have resulted in higher peak torque and likely higher peak RTD values as well. Faster activation could have also been expected to shorten EMD and times to peak RTD and peak torque. As none of these functional changes occurred in our trained subjects, the functional and discriminatory significance of Q_{30} is unclear.

It should be noted that the trained boys group in this study consisted only of only, while the trained men’s group also included triathletes. It may be argued that swimming may emphasize the muscles of the upper limbs, while cycling and running train only the lower limbs, thereby differentially affecting the training effects in each of the two age groups. Nevertheless, in spite of the greater lower-limbs emphasis in the adult endurance group, no apparent training effect was detected in knee flexion or extension. This was also apparent in the upper limbs. Furthermore, the pattern of higher rate of activation observed in the adults’, but not boys’ trained group was also apparent in the upper limbs. Thus, it appears that the difference in subject make-up of the two age groups strengthens rather than weakens the claim that endurance training does not affect muscle force and dynamics.

In summary, during maximal voluntary isometric muscle contractions men were stronger, had higher RTD and Q_{30} than the boys, in both absolute and size-normalized values, and had shorter EMD and time-to-peak RTD. Endurance-training could only be shown to have affected a higher Q_{30} in the men with no corresponding performance differences in any of the measured variables. Thus, Q_{30}’s functional and discriminatory significance is unclear, at least in as much as endurance training is concerned. It thus appears that the functional effects of endurance training are mainly confined to the metabolic realm.

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FIGURE LEGENDS

Figure 1: Knee extension peak torque of the endurance-trained and untrained boys and men. A. Peak torque in absolute values. B. Peak torque corrected to body mass. Data are presented as Mean±SD. *p<0.05, Ψ=age*training interaction (P<0.05).

Figure 2: Knee extension rate of torque development (RTD) of the endurance-trained and untrained boys and men. A. RTD in absolute values, B. RTD corrected to peak torque. Data are presented as Mean±SD. *p<0.05.

Figure 3: Knee extension rate of rise of EMG activity (Q_{30}) in the endurance-trained and untrained boys and men. A. Q_{30} in absolute values, B. Q_{30} corrected to peak EMG amplitude, Data are presented as Mean±SD. *p<0.05, Ψ=age*training interaction (P<0.05). The p value for age-by-training interaction for the normalized Q_{30} was 0.090.

Figure 4: A. Knee-extension time to peak torque of the endurance-trained and untrained boys and men. B. Knee extension time to peak RTD of the endurance-trained and untrained boys and men. Data are presented as Mean±SD. *p<0.05.

Figure 5: Knee-extension EMD in endurance-trained and untrained boys and men. Data are presented as Mean±SD. *p<0.05.

REFERENCES

1998. American College of Sports Medicine Position Stand. The recommended quantity and quality of exercise for developing and maintaining cardiorespiratory and muscular fitness, and flexibility in healthy adults. Med Sci Sports Exerc 30(6):975-991.

Aagaard P. 2003. Training-induced changes in neural function. Exerc Sport Sci Rev 31(2):61-67.

Aagaard P, Simonsen EB, Andersen JL, Magnusson P, and Dyhre-Poulsen P. 2002. Increased rate of force development and neural drive of human skeletal muscle following resistance training. J Appl Physiol 93(4):1318-1326.

Armstrong N, Barrett LA, and Welsman JR. 2007. Cardiorespiratory training during childhood and adolescence. Journal of Exercise Science and Physiotherapy 3:67-75.

Asai H, and Aoki J. 1996. Force development of dynamic and static contractions in children and adults. Int J Sports Med 17(3):170-174.

Baxter-Jones AD, Eisenmann JC, Mirwald RL, Faulkner RA, and Bailey DA. 2008. The influence of physical activity on lean mass accrual during adolescence: a longitudinal analysis. J Appl Physiol 105(2):734-741.

Behm DG, Faigenbaum AD, Falk B, and Klentrou P. 2008. Canadian Society for Exercise Physiology position paper: resistance training in children and adolescents. Appl Physiol Nutr Metab 33(3):547-561.

Belanger AY, and McComas AJ. 1989. Contractile properties of human skeletal muscle in childhood and adolescence. Eur J Appl Physiol Occup Physiol 58(6):563-567.

Bencke J, Damsgaard R, Saekmose A, Jorgensen P, Jorgensen K, and Klausen K. 2002. Anaerobic power and muscle strength characteristics of 11 years old elite and non-elite boys and girls from gymnastics, team handball, tennis and swimming. Scand J Med Sci Sports 12(3):171-178.

Buchanan CI, and Marsh RL. 2001. Effects of long-term exercise on the biomechanical properties of the Achilles tendon of guinea fowl. J Appl Physiol 90(1):164-171.

Cavanagh PR, and Komi PV. 1979. Electromechanical delay in human skeletal muscle under concentric and eccentric contractions. Eur J Appl Physiol Occup Physiol 42(3):159-163.

Cornu C, and Goubel F. 2001. Musculo-tendinous and joint elastic characteristics during elbow flexion in children. Clin Biomech (Bristol, Avon) 16(9):758-764.

De Ste Croix MBA, Armstrong N, and Welsman JR. 1999. Concentric isokinetic leg strength in pre-teen, teenage and adult males and females. Biology of Sport 16:75-88.

Delagi EF, and Perotto A. 1980. Anatomic guide for the electromyographer. Springfield, IL: CC Thomas.

Dubowitz V. 1965. Enzyme histochemistry of skeletal muscle. J Neurol Neurosurg Psychiatry 28(6):516-524.

Duke PM, Litt IF, and Gross RT. 1980. Adolescents' self-assessment of sexual maturation. Pediatrics 66(6):918-920.

Durnin JV, and Womersley J. 1974. Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. Br J Nutr 32(1):77-97.

Dvir Z. 2004. Isokinetics: muscle testing, interpretation, and clinical applications. New York: Churchill Livingstone.

Falk B, Brunton L, Dotan R, Usselman C, Klentrou P, and Gabriel D. 2009a. Muscle strength and contractile kinetics of isometric elbow flexion in girls and women. Pediatr Exerc Sci 21(3):354-364.

Falk B, and Dotan R. 2006. Child-adult differences in the recovery from high-intensity exercise. Exerc Sport Sci Rev 34(3):107-112.

Falk B, Usselman C, Dotan R, Brunton L, Klentrou P, Shaw J, and Gabriel D. 2009b. Child-adult differences in muscle strength and activation pattern during isometric elbow flexion and extension. Appl Physiol Nutr Metab 34(4):609-615.

Gabriel DA, and Boucher JP. 2000. Practicing a maximal performance task: a cooperative strategy for muscle activity. Res Q Exerc Sport 71(3):217-228.

Godin G, and Shephard RJ. 1985. A simple method to assess exercise behavior in the community. Can J Appl Sport Sci 10(3):141-146.

Gottlieb GL, Corcos DM, and Agarwal GC. 1989. Organizing principles for single-joint movements. I. A speed-insensitive strategy. J Neurophysiol 62(2):342-357.

Grosset JF, Mora I, Lambertz D, and Perot C. 2005. Age-related changes in twitch properties of plantar flexor muscles in prepubertal children. Pediatr Res 58(5):966-970.

Grosset JF, Mora I, Lambertz D, and Perot C. 2008. Voluntary activation of the triceps surae in prepubertal children. J Electromyogr Kinesiol 18(3):455-465.

Grosset JF, Piscione J, Lambertz D, and Perot C. 2009. Paired changes in electromechanical delay and musculo-tendinous stiffness after endurance or plyometric training. Eur J Appl Physiol 105(1):131-139.

Halin R, Germain P, Bercier S, Kapitaniak B, and Buttelli O. 2003. Neuromuscular response of young boys versus men during sustained maximal contraction. Med Sci Sports Exerc 35(6):1042-1048.

Halin R, Germain P, Buttelli O, and Kapitaniak B. 2002. Differences in strength and surface electromyogram characteristics between pre-pubertal gymnasts and untrained boys during brief and maintained maximal isometric voluntary contractions. Eur J Appl Physiol 87(4-5):409-415.

Hatzikotoulas K, Patikas D, Bassa E, Paraschos I, and Kotzamanidis C. 2008. Differences in voluntary activation between adult and prepubertal males. In: Jurimae T, Armstrong N, and Jurimae J, editors. Children and Exercise XXIV: The Proceedings of the 24th Pediatric Work Physiology Meeting. Talinn, Estonia: Routledge. p 247-251.

Holtermann A, Roeleveld K, Vereijken B, and Ettema G. 2007. The effect of rate of force development on maximal force production: acute and training-related aspects. Eur J Appl Physiol 99(6):605-613.

Janz KF, Dawson JD, and Mahoney LT. 2002. Increases in physical fitness during childhood improve cardiovascular health during adolescence: the Muscatine Study. Int J Sports Med 23 Suppl 1:S15-21.

Kellis E, and Baltzopoulos V. 1996. Resistive eccentric exercise: effects of visual feedback on maximum moment of knee extensors and flexors. J Orthop Sports Phys Ther 23(2):120-124.

Kubo K, Kanehisa H, Kawakami Y, and Fukunaga T. 2000. Elastic properties of muscle-tendon complex in long-distance runners. Eur J Appl Physiol 81(3):181-187.

Lambertz D, Mora I, Grosset JF, and Perot C. 2003. Evaluation of musculotendinous stiffness in prepubertal children and adults, taking into account muscle activity. J Appl Physiol 95(1):64-72.

Lattier G, Millet GY, Maffiuletti NA, Babault N, and Lepers R. 2003. Neuromuscular differences between endurance-trained, power-trained, and sedentary subjects. J Strength Cond Res 17(3):514-521.

Lucia A, Hoyos J, Pardo J, and Chicharro JL. 2000. Metabolic and neuromuscular adaptations to endurance training in professional cyclists: a longitudinal study. Jpn J Physiol 50(3):381-388.

Maffulli N, King JB, and Helms P. 1994. Training in elite young athletes (the Training of Young Athletes (TOYA) Study): injuries, flexibility and isometric strength. Br J Sports Med 28(2):123-136.

Mirwald RL, Baxter-Jones AD, Bailey DA, and Beunen GP. 2002. An assessment of maturity from anthropometric measurements. Med Sci Sports Exerc 34(4):689-694.

Morse CI, Tolfrey K, Thom JM, Vassilopoulos V, Maganaris CN, and Narici MV. 2008. Gastrocnemius muscle specific force in boys and men. J Appl Physiol 104(2):469-474.

O'Brien TD, Reeves ND, Baltzopoulos V, Jones DA, and Maganaris CN. 2009. The effects of agonist and antagonist muscle activation on the knee extension moment-angle relationship in adults and children. Eur J Appl Physiol 106(6):849-856.

Ozmun JC, Mikesky AE, and Surburg PR. 1994. Neuromuscular adaptations following prepubescent strength training. Med Sci Sports Exerc 26(4):510-514.

Paasuke M, Ereline J, and Gapeyeva H. 2000. Twitch contraction properties of plantar flexor muscles in pre- and post-pubertal boys and men. Eur J Appl Physiol 82(5-6):459-464.

Pang MY, Eng JJ, Dawson AS, and Gylfadottir S. 2006. The use of aerobic exercise training in improving aerobic capacity in individuals with stroke: a meta-analysis. Clin Rehabil 20(2):97-111.

Ramsay JA, Blimkie CJ, Smith K, Garner S, MacDougall JD, and Sale DG. 1990. Strength training effects in prepubescent boys. Med Sci Sports Exerc 22(5):605-614.

Sale DG. 1988. Neural adaptation to resistance training. Med Sci Sports Exerc 20(5 Suppl):S135-145.

Slaughter MH, Lohman, T. G., Boileau, B.A. 1988. Skinfold equations for estimation of body fatness in children and youth. Hum Biol 60:709-723.

Sleivert GG, Backus RD, and Wenger HA. 1995. Neuromuscular differences between volleyball players, middle distance runners and untrained controls. Int J Sports Med 16(6):390-398.

Smits-Engelsman BC, Westenberg Y, and Duysens J. 2003. Development of isometric force and force control in children. Brain Res Cogn Brain Res 17(1):68-74.

Stenevi-Lundgren S, Daly RM, Linden C, Gardsell P, and Karlsson MK. 2009. Effects of a daily school based physical activity intervention program on muscle development in prepubertal girls. Eur J Appl Physiol 105(4):533-541.

Streckis V, Skurvydas A, and Ratkevicius A. 2007. Children are more susceptible to central fatigue than adults. Muscle Nerve 36(3):357-363.

Tanner JM. 1962. Growth at Adolescence. Oxford: Blackwell Scientific Publications.

Van Cutsem M, Duchateau J, and Hainaut K. 1998. Changes in single motor unit behaviour contribute to the increase in contraction speed after dynamic training in humans. J Physiol 513 (Pt 1):295-305.

Zakas A. 2004. The effect of cycle ergometer strength training in prepubertal untrained males. Pediatr Exerc Sci 16(2):368-377.

Figure 1

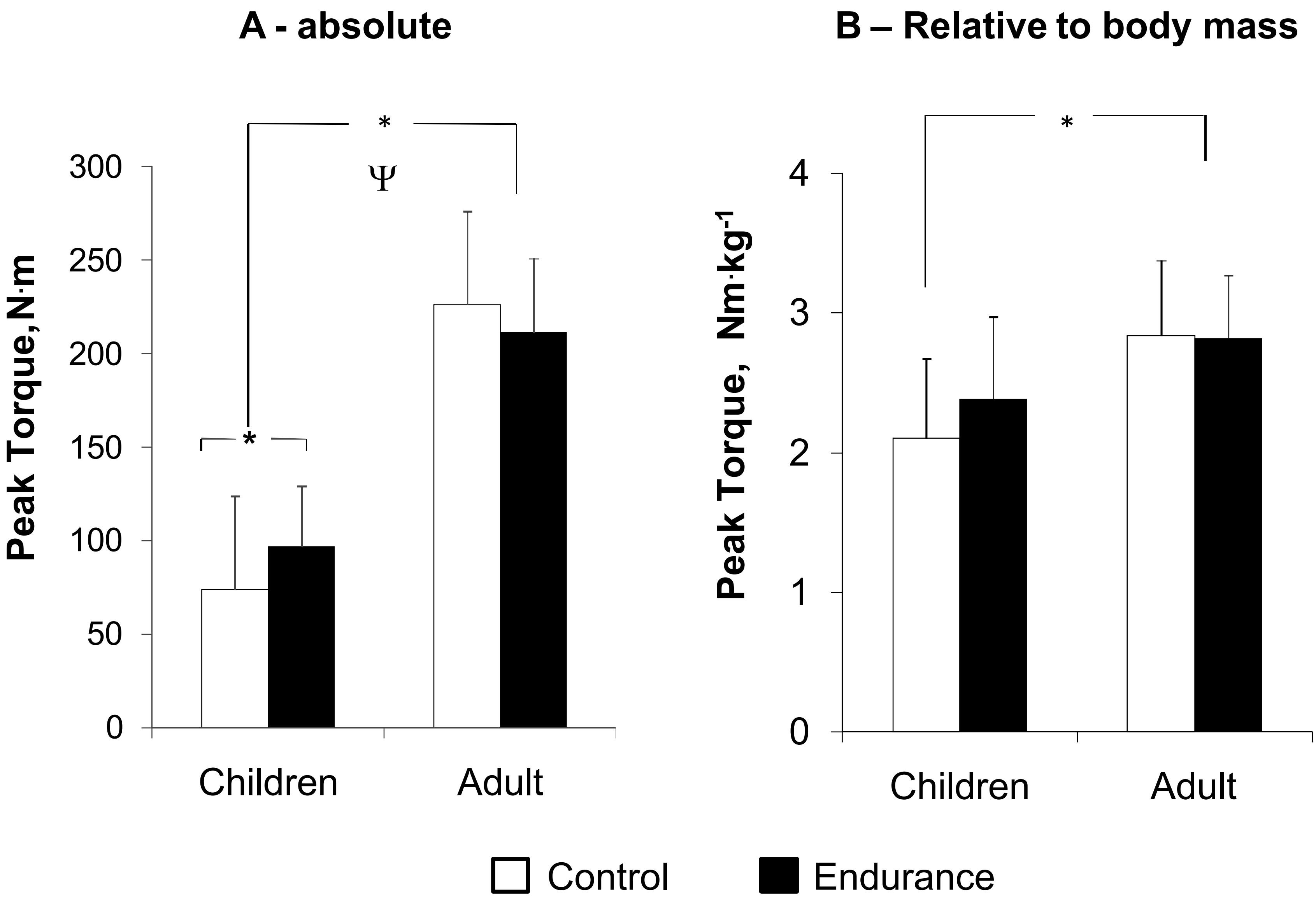
A - absolute
B – Relative to body mass
Peak Torque, N·m
Peak Torque, Nm·kg-1
300
250
200
150
100
50
0
4
3
2
1
0
*
Ψ
*
*
Children
Adult
Children
Adult
☐ Control
■ Endurance

Figure 2

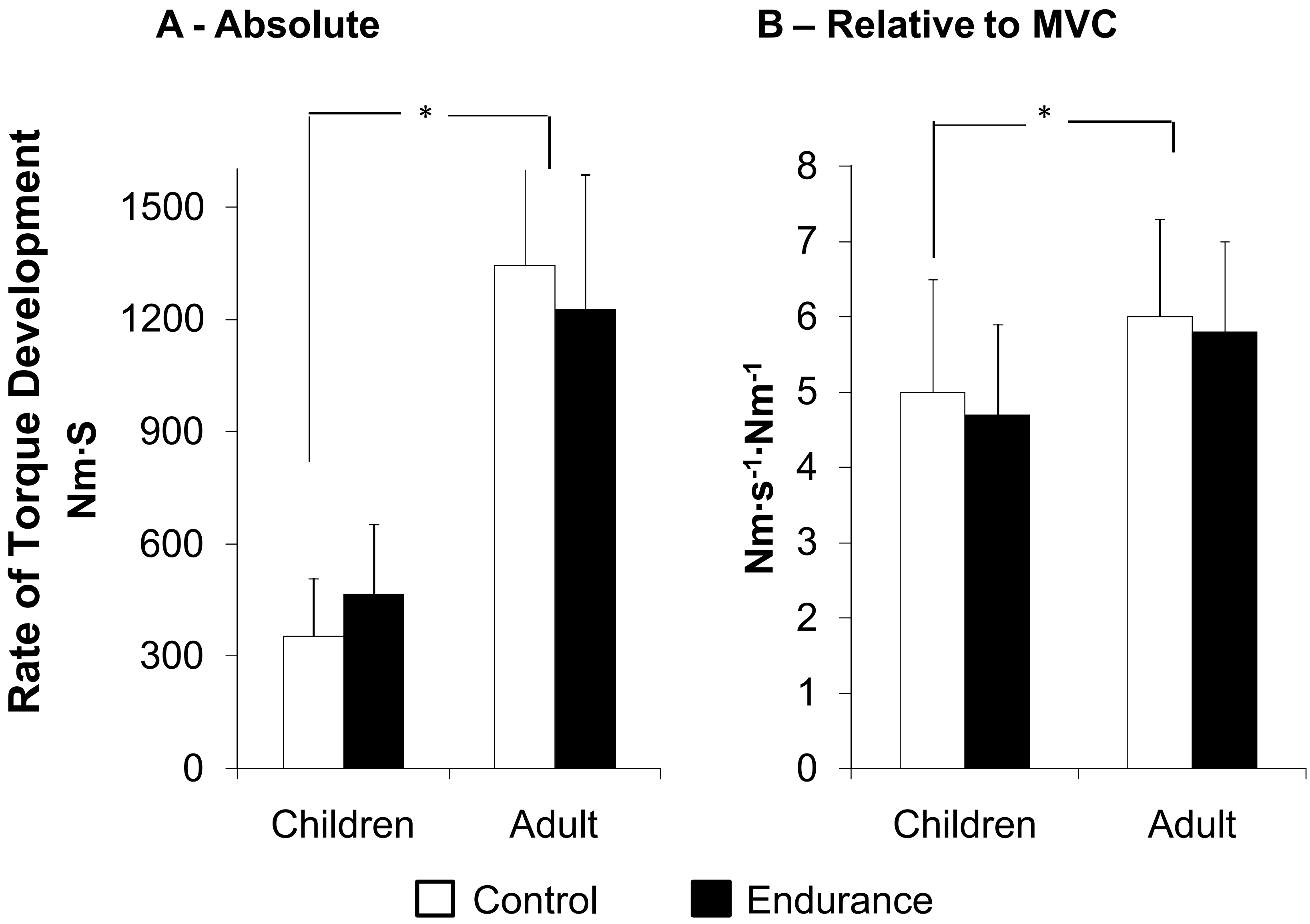
A - Absolute
B – Relative to MVC
*
*
Rate of Torque Development
Nm·S
1500
1200
900
600
300
0
Nm·s-1·Nm-1
8
7
6
5
4
3
2
1
0
Children
Adult
Children
Adult
☐ Control
■ Endurance

Figure 3

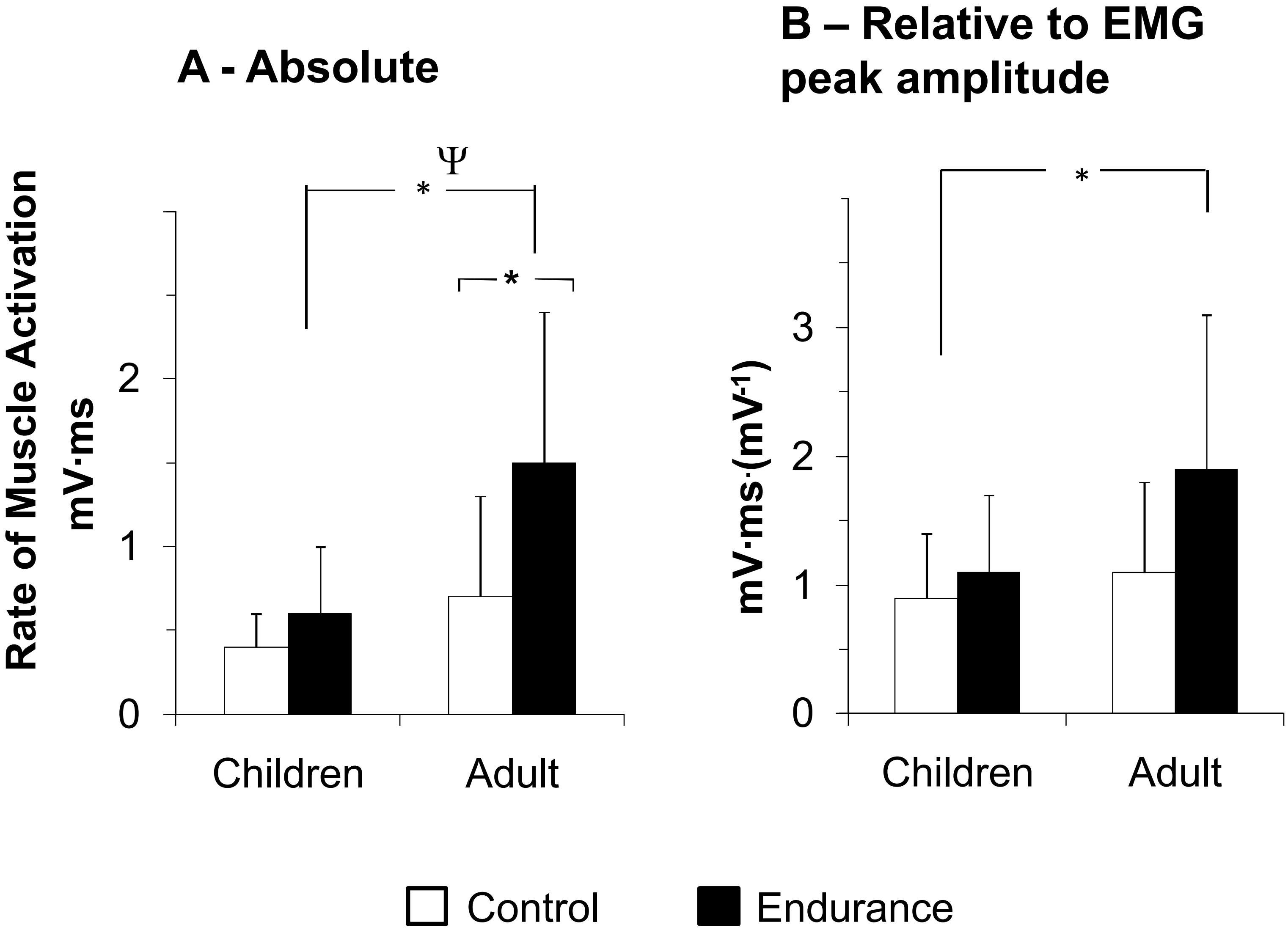
A - Absolute
B – Relative to EMG peak amplitude
Rate of Muscle Activation
mV·ms
0
1
2
Children
Adult
Ψ
*
*
mV·ms·(mV-1)
0
1
2
3
Children
Adult
*
Control
Endurance

Figure 4

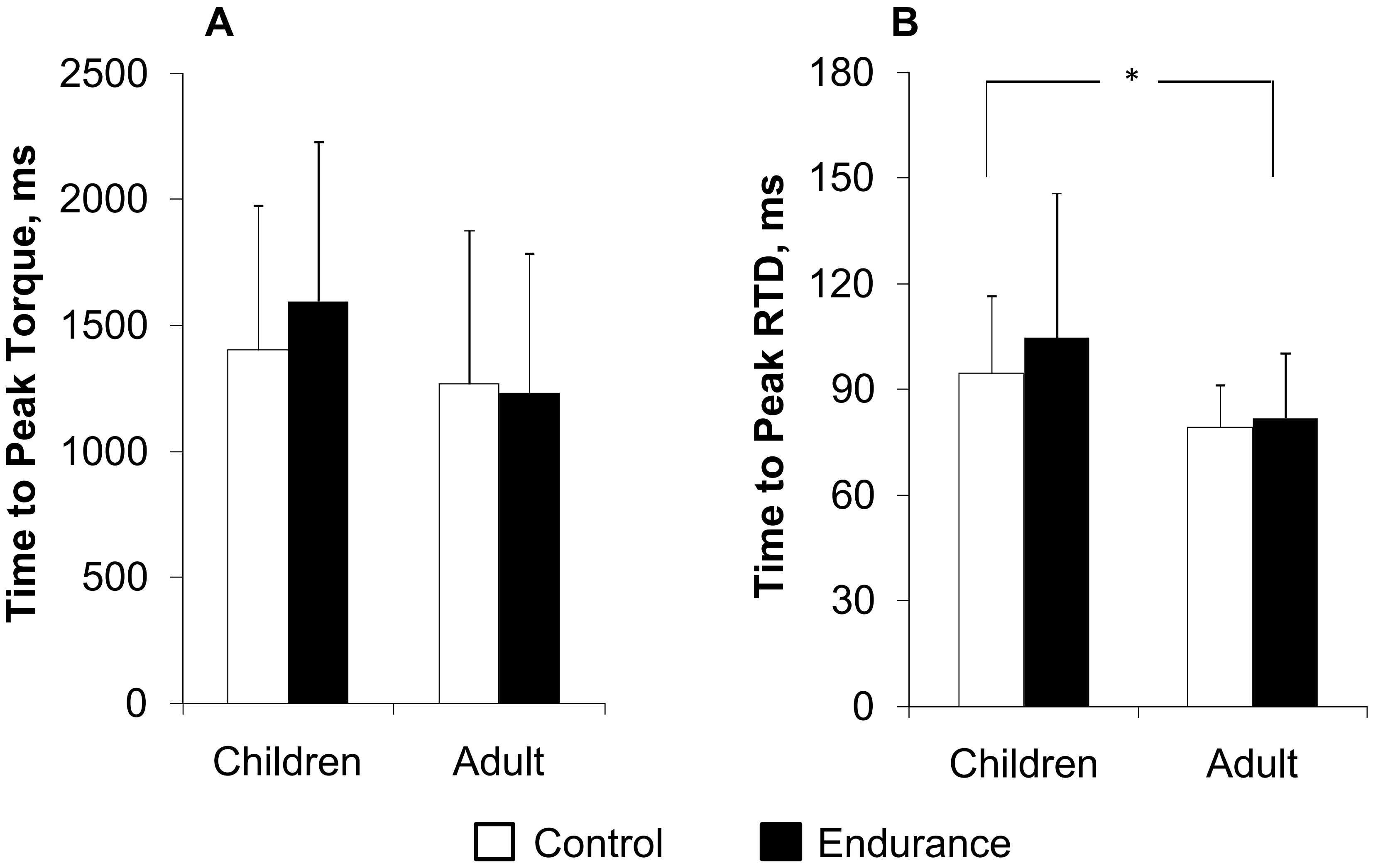
A
Time to Peak Torque, ms
2500
2000
1500
1000
500
0
Children
Adult
B
Time to Peak RTD, ms
180
150
120
90
60
30
0
*
Children
Adult
□ Control
■ Endurance

Figure 5

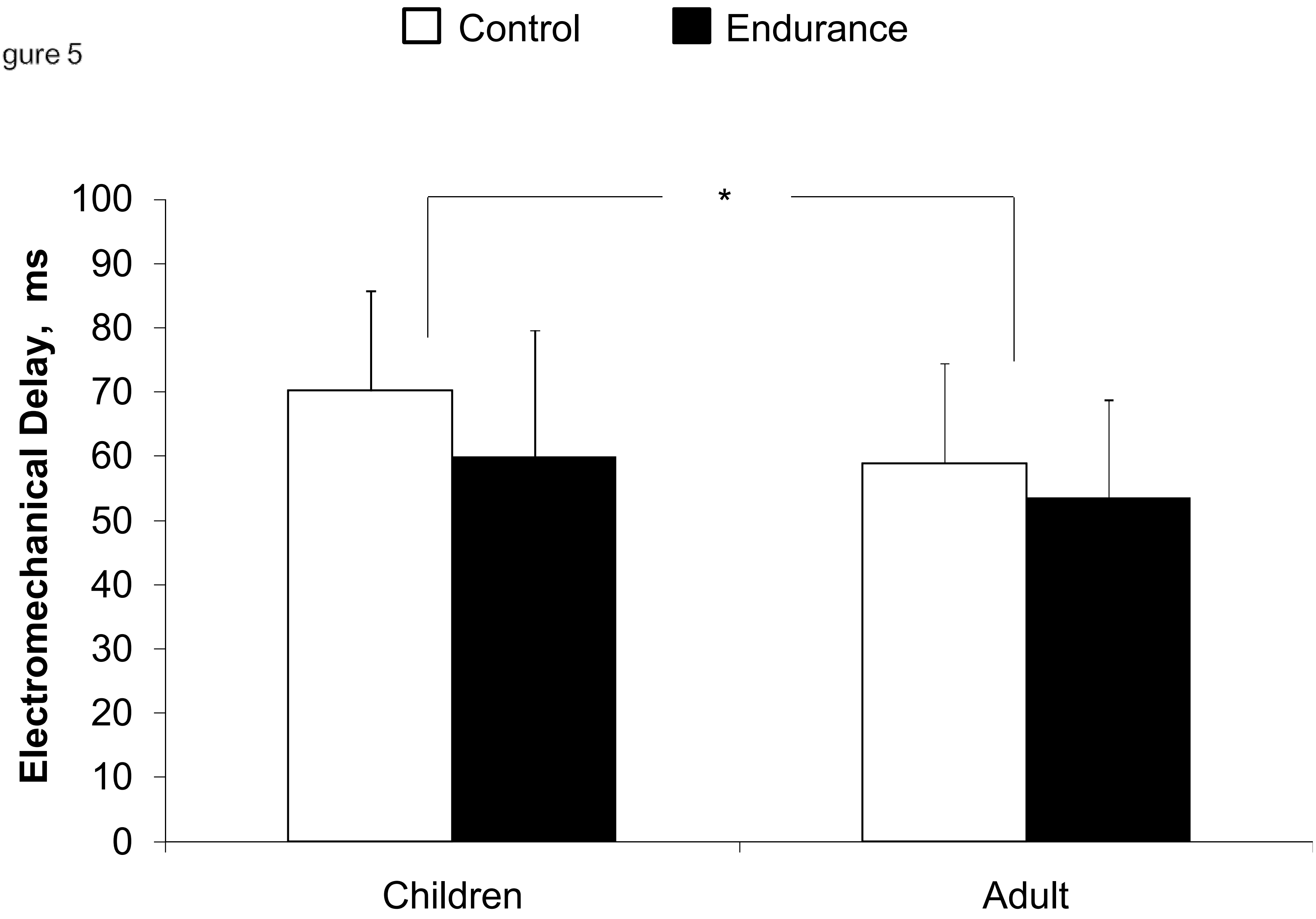
☐ Control
■ Endurance
Electromechanical Delay, ms
100
90
80
70
60
50
40
30
20
10
0
*
Children
Adult

Table 1: Physical characteristics of the endurance-trained and untrained boys and men

	Children		**Adults**	
	Control (n=16)	Endurance (n=12)	Control (n=20)	Endurance (n=15)
Age (yrs)	10.2 ± 1.0^{a}	10.7 ± 0.7^{b}	22.8 ± 4.4^{a}	24.5 ± 5.9^{b}
Tanner (I,II,III,IV,V)	9,7,0,0,0	7,5,0,0,0	-	-
Years from Peak Height Velocity	-3.1 ± 0.8	-2.5 ± 0.7	-	-
Height (cm)	141.5 ± 8.6^{a}	145.9 ± 7.2^{b}	180.5 ± 7.4^{a}	179.2 ± 5.7^{b}
Weight (kg)	35.7 ± 8.0^{a,c}	41.5 ± 12.6^{b,c}	80.4 ± 12.4^{a,d}	74.7 ± 6.0^{b,d}
Body Fat percentage (%)	18.1 ± 6.6	20.1 ± 12.0	17.9 ± 4.8	14.8 ± 3.8
Lean body mass (kg)	28.8 ± 4.6^{a}	31.9 ± 5.2^{b}	65.6 ± 8.1^{a}	63.5 ± 5.1^{b}

Values are presented as M ± SD. Similar superscripts indicate pairwise significant differences ($p < 0.05$).

Similar letters display significant difference between groups.

Table 2: Repeated measures including all four types of contractions

		Age effect	Training effect	Age*training interaction
Torque:	Absolute	<0.001	-	0.030
	Per Kg	<0.001	-	-
RTD:	Absolute	<0.001	-	-
	Per torque	<0.001	-	-
Q_{30}:	Absolute	<0.001	-	-
	Per EMG_{amp}	<0.001	-	0.032
T to peak torque		0.002	-	-
T to peak RFD		<0.001	-	-
EMD		<0.001	-	-
Co-activation		0.013	0.031	-