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# **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

## 1 **Abstract**

2           Most research on the effects of endurance training has focused on its health-related  
3 benefits and metabolic effects in both children and adults. The purpose of this study was to  
4 examine neuromuscular effects of endurance training and whether they differ in children (9.0-  
5 12.9 yrs) compared with adults (18.4-35.6 yrs). Maximal isometric torque, rate of torque  
6 development (RTD), rate of muscle activation ( $Q_{30}$ ), electro-mechanical delay (EMD), and time  
7 to peak torque and peak RTD were determined by isokinetic dynamometry and surface  
8 electromyography, in elbow and knee flexion and extension. Subjects were 12 endurance-trained  
9 and 16 untrained boys, and 15 endurance-trained and 20 untrained men. Adults displayed  
10 consistently higher peak torque, RTD, and  $Q_{30}$ , in both absolute and normalized values, while  
11 boys had longer EMD ( $64.7 \pm 17.1$  vs.  $56.6 \pm 15.4$  ms) and time to peak RTD ( $98.5 \pm 32.1$  vs.  
12  $80.4 \pm 15.0$  ms for boys and men, respectively).  $Q_{30}$ , normalized for peak EMG amplitude, was the  
13 only observed training effect ( $1.95 \pm 1.16$  vs.  $1.10 \pm 0.67$  ms for trained and untrained men,  
14 respectively). This effect could not be shown in the boys. The findings show normalized muscle  
15 strength and rate of activation to be lower in children compared with adults, regardless of  
16 training status. As observed higher  $Q_{30}$  values were not matched by corresponding higher  
17 performance measures in the trained men, the functional and discriminatory significance of  $Q_{30}$   
18 remains unclear. Endurance training does not appear to affect muscle strength or rate of force  
19 development in either men or boys.

20

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

1

## 2 INTRODUCTION

3 Previous research on the effects of endurance-type training has focused mainly on health-  
4 related benefits and physiological adaptations related to aerobic capacity. The focus on  
5 cardiovascular health and metabolic adaptations to endurance training is evident in the adult  
6 (1998; Pang et al. 2006), as well as in the pediatric literature (Armstrong et al. 2007; Janz et al.  
7 2002). Corresponding research on neuromuscular adaptations to endurance-type training is  
8 notably lacking.

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

21 It has been suggested that the capacity of pre-pubertal boys to activate their  
22 neuromuscular system is lower than that of adults (Belanger and McComas 1989; Grosset et al.  
23 2008; Hatzikotoulas et al. 2008; O'Brien et al. 2009; Paasuke et al. 2000), and that children are

1 less capable of recruiting or utilizing their higher-threshold motor units (Asai and Aoki 1996;  
2 Falk and Dotan 2006; Falk et al. 2009b). While not all studies have demonstrated a lower motor  
3 unit activation in children (Streckis et al. 2007), Halin et al. (Halin et al. 2002) proposed that  
4 children's neuromuscular system may be more adaptive to a training stimulus compared with  
5 adults.

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

## 9 **METHODS**

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

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

3 Those subjects who had prior or present conditions that could affect muscle or  
4 neuromuscular function (e.g muscular disease, use of medications, and injury to dominant  
5 hand/leg) were excluded from the study.

6 **Procedures:** All tests and measurements were performed during two visits to the laboratory.  
7 Subjects were instructed to refrain from excessive exercise the day preceding the testing.

8 On the first visit, subjects were informed of the purpose, methods, and potential risks of  
9 the study. Before testing, an informed consent form was signed by the participant or by the  
10 children's parents. Subsequently, anthropometric measurements (mass, height, sitting height and  
11 skinfold thickness) were assessed, and questionnaires (medical, physical activity, pubertal stage)  
12 were filled out. Subjects then performed a shorter version of the testing protocol in order to  
13 become familiar with the instructions, equipments and the testing procedure. These data were not  
14 used for analysis. The initial setting on the dynamometer was individually adjusted and the  
15 position of all dynamometer attachments was recorded in order to be used during the second  
16 visit. On the second visit, subjects performed only the strength testing protocol along with  
17 electromyography signal (EMG) acquisition.

18 **Anthropometric measurements:** Height and body mass were measured using an Ellard  
19 Instrumentation board length stadiometer (Monroe, WA, USA) and a digital scale (Zenith),  
20 respectively with subjects in light clothing and no shoes. Height and body mass were recorded to  
21 the nearest 0.1 cm and 0.1kg, respectively. Sitting height was also recorded in order to estimate  
22 the age of peak height velocity, reflecting somatic maturity (Mirwald et al. 2002). Skinfold  
23 thickness was measured in triplicate using Harpenden calipers (British Indicators, Herts,

1 England) and the median value at each site was used. The following sites were evaluated: biceps,  
2 triceps, subscapular and suprailiac. Adiposity (percentage of body fat) was estimated from the  
3 appropriate skinfold measurements, using age- and maturity-specific equations (Durnin and  
4 Womersley 1974; Slaughter 1988). All measurements were performed by the same investigator.  
5 The coefficient of variance (CV) was 5% and the intra-observer reliability (ICC) in 10 subjects  
6 was  $r = 0.98$ .

7 **Pubertal stage:** Pubertal status was determined using secondary sex characteristics (pubic hair),  
8 as described by (Tanner 1962). Pubertal stage was self-reported, using drawings (Duke et al.  
9 1980). The self-assessment form was placed in an envelope by the subject and handed directly to  
10 the researcher, to assure discreetness.

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

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

1 (Falk et al. 2009a; Falk et al. 2009b). In order to reduce the noise on the recorded torque channel,  
2 an EMG/analog signal access interface (Biodex, Shirley, NY) was used. This utility configures  
3 the scale factors of the analog signal outputs for torque. For each participant the scaling factor  
4 was adjusted according to the torque values reached in the habituation session during the first  
5 visit.

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

12 For the lower limbs, subjects sat upright in a chair with hip angle of 120°, and the knee at  
13 90° of flexion. The ankle was secured (using Velcro straps) to an adjustable lever arm. The  
14 torque axis was aligned with the lateral femoral epicondyle. After adjustments, subjects were  
15 secured in the chair to prevent stabilizing movements that could affect the measurements with  
16 two straps secured across the chest and another strap across the thigh.

17 The testing protocol included a specific warm-up (~5 contractions of progressive  
18 intensity), followed by two sets of five 3-seconds maximal voluntary contractions (MVC). A 30-  
19 seconds rest followed each repetition. Rest between each set was 2 minutes. The order of the sets  
20 (flexion/extension, upper/lower limb) was counterbalanced between subjects. Additional  
21 repetitions were performed as needed, to reach at least 5 valid trials. Data were deemed  
22 unacceptable due to execution errors, deviations in EMG baseline, or abnormal torque or EMG  
23 amplitudes. Each subject was instructed to contract “as hard and as fast as possible” from a

1 relaxed state to ensure maximal torque and rate of torque development (RTD). Subjects were  
2 verbally encouraged to perform a maximal effort throughout each contraction. Online visual  
3 feedback of the dynamometer's torque signal was available for the subjects on a PC screen.  
4 Visual feedback has been shown to be important for torque production (Kellis and Baltzopoulos  
5 1996), especially in young children (Smits-Engelsman et al. 2003). Peak torque was recorded  
6 from the dynamometer system and stored for off-line analysis.

7 **Electromyography (EMG):** During each contraction, EMG signals were collected from the  
8 agonist and antagonist muscles using bipolar surface electrodes (Delsys 2.1, Delsys Inc., Boston,  
9 MA). In the upper limbs, electrodes were placed on the muscle belly midsections of the biceps  
10 brachii and the lateral head of the triceps brachii. In the lower limbs, electrodes were placed on  
11 the muscle belly of the vastus lateralis and biceps femoris. These were determined visually  
12 during a resisted static contraction. The electrodes were placed in line with the muscle fibres,  
13 away from the estimated motor point (Delagi and Perotto 1980). A ground electrode served as a  
14 reference electrode and was placed over the clavicle.

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

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

22 **Data Reduction and Analysis:** Using EGGLAB and MatLab (The MathWorks, Natick, MA),  
23 several variables were calculated for each type of movement tested. Mean traces of the best five

1 trials of EMG agonist, EMG antagonist and torque were created in order to reduce signal-to-  
2 noise ratio. Torque and EMG traces in each set were visually examined. Inclusion for analysis  
3 was based on clear and stable EMG baseline prior to the beginning of the contraction and clear  
4 onset of torque and EMG activity. Any faulty trials were eliminated and out of the remaining  
5 trials, the best five repetitions were used for analysis, based on the highest peak torques and RTD  
6 values. The intra-session reliability for agonist EMG amplitude reliability coefficient ( $ICC_{2,1}$ )  
7 was 0.65 and 0.94 for boys and men, respectively.

8         Traces were time-locked on the torque onset and averaged. The average waveform  
9 consisted of 400 ms prior to the force onset and 3000 ms afterwards. The mean traces were used  
10 to calculate peak torque, RTD, rate of rise of muscle activation ( $Q_{30}$ ), electro-mechanical delay  
11 (EMD), time to peak torque, time to peak RTD, and agonist-antagonist co-activation. Peak RTD  
12 was calculated by taking the maximum of the 1st derivative of the torque signal (Gabriel et al.  
13 2001). Agonist and antagonist EMG amplitudes were calculated from the detected linear  
14 envelope. The peak EMG amplitudes values were calculated over 250ms around the time of  
15 occurrence of peak torque.  $Q_{30}$  was measured over the first 30ms of electromechanical activity.  
16  $Q_{30}$  was defined as the area under the linear envelope of the detected EMG signal during the  
17 initial 30 ms (Gabriel and Boucher 2000; Gottlieb et al. 1989), and has been previously used to  
18 reflect rate of increase in muscle activation during a maximal task (Falk et al. 2009a; Falk et al.  
19 2009b; Gabriel and Boucher 2000; Gottlieb et al. 1989). The EMG activity onset was defined as  
20 the point in time at which the signal first increased 5 standard deviations above the mean of the  
21 baseline and stayed above that point for more than 20 msec. The onset of torque was defined as  
22 the first point in time where the RTD reached 5 standard deviations of the baseline mean for at  
23 least 10 ms. This point was confirmed visually and adjusted manually if needed. EMD was

1 defined as the delay, in ms, between the agonist EMG activity onset and the onset of torque  
2 production. The time to peak torque was calculated as the time delay (ms) between the onset of  
3 torque generation and the occurrence of peak torque. The time to peak RTD was calculated as  
4 the time delay (ms) between the onset of torque generation and the occurrence of peak RTD. Co-  
5 activation was calculated as the ratio between the antagonist's EMG amplitude divided by its  
6 EMG amplitude as an agonist (i.e., for knee extension: [Biceps femoris EMG amplitude in knee  
7 extension] / [Biceps femoris EMG amplitude in knee flexion]).

8 **Statistical Analysis:** All statistical analyses were performed using SPSS v.16 (SPSS Inc.,  
9 Chicago, IL). The data for all groups are presented as mean (M)  $\pm$ 1 standard deviation (SD). The  
10 data were cleaned by checking for outliers ( $>2$  standard deviations from the mean) of all  
11 dependent variables for each of the four contractions. In total, four outlying values were found  
12 (one value of Q<sub>30</sub> in each of the four contraction modes) and were not included in the analysis. A  
13 Chi square analysis was used to compare the pubertal stage distributions. Group differences in  
14 muscle performance and neuromuscular function were determined using a two-way analysis of  
15 variance (ANOVA), with training and age as the between-subjects main effects. *Post hoc*  
16 comparisons (LSD) were performed when a main effect or interaction was found to be  
17 statistically significant. Each contraction was analyzed separately. Subsequently, all contractions  
18 were analyzed together using two-way ANOVA for repeated measures to identify general  
19 patterns. The acceptable level of significance was set at  $p < 0.05$ .

## 20 RESULTS

21 The physical characteristics of the subjects are displayed in table 4.1. The men were  
22 older, taller, and heavier, with greater lean body mass than the children. There was no significant  
23 difference in age or height between the untrained control boys and the endurance-trained boys

1 groups as well as between the untrained control adult and the endurance-trained adult groups.  
2 There was an age-by-training interaction for body mass, reflecting the fact that among the boys,  
3 the endurance-trained boys were heavier, while among the adults, the pattern was reversed.  
4 There were no significant differences between and within the age groups in relative body fat.  
5 There were no significant differences in sexual maturation stage and years from age of peak  
6 height velocity between the two boys groups (Table 1).

7 [Table 1]

8 There was a significant difference in training hours between groups. The adults trained  
9  $14.4 \pm 5.0$  hr/wk while the boys trained  $8.5 \pm 3.6$  hr/wk. Both the men and the boys participated in  
10 dry-land training which included limited resistance exercise in addition to their endurance-  
11 training program ( $2.5 \pm 1.3$  hr/wk and  $3.4 \pm 1.5$  hr/wk, respectively).

12 Data for all four contraction modes (elbow flexion and extension, knee flexion and  
13 extension) were collected. Since the pattern of results was similar in all four types of  
14 contractions, for the purpose of simplicity only knee extension data are presented within the text.  
15 The results of all contraction modes are summarized in Table 2 (see below).

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

22 [Figure 1a,b]



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

3 [Figure 5]

4 The co-activation index was low in all groups and similar in the trained and untrained  
5 boys ( $0.15\pm 0.17$  and  $0.11\pm 0.05$ , respectively), as well as in the trained and untrained men  
6 ( $0.09\pm 0.07$  and  $0.13\pm 0.06$ , respectively). No age effect or age-by-training interactions were  
7 found.

8 *Repeated measures analysis:* Table 2 presents the results of the ANOVA for repeated measures  
9 analysis highlighting only the significant effects. An age effect was apparent in all variables  
10 examined, which reflects the fact that the pattern of age differences was a persistent finding  
11 across all four modes of contractions tested. On average, the men had higher torque, RTD and  
12  $Q_{30}$  values than the boys, whether those variables were expressed in absolute or normalized  
13 values. Furthermore, EMD, time to peak RTD and peak torque were significantly longer in boys  
14 compared with men. The co-activation index was lower in men compared with boys. In addition,  
15 the training effect was apparent only in co-activation index, which reflects the fact that on  
16 average the athletes had lower co-activation index than the untrained subjects. However, it  
17 should be noted that generally, co-activation indices were very low ( $<0.20$ ) in all groups.

18 There was an age-by-training interaction for absolute peak torque, reflecting the fact that  
19 the endurance-trained boys were significantly stronger than their age-matched untrained controls.  
20 This was not the case in the men. When peak torque was normalized for body mass, no training  
21 effect or interactions were observed. There was an age-by-training interaction when  $Q_{30}$  was  
22 normalized to peak EMG amplitude. This interaction reflects the fact that the endurance-trained

1 men had higher  $Q_{30}$  values than their age matched control subjects, while no such difference was  
2 apparent between the two boys groups.

3 [Table 2]

#### 4 **DISCUSSION**

5 We compared maximal isometric torque, rate of torque development, and rate of muscle  
6 activation of elbow and knee flexion and extension, in endurance-trained and minimally-active  
7 boys and men. Our main results showed that men were stronger, had higher RTD and  $Q_{30}$  than  
8 the boys, whether expressed in absolute values or normalized to body mass, peak torque or peak  
9 EMG amplitude, respectively. No training-related muscle-performance differences were  
10 observed but trained men had significantly higher  $Q_{30}$  compared with the untrained men. While  
11  $Q_{30}$  also tended to be higher in the trained boys, the difference was not statistically significant.

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

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

22 Age-related differences in muscle fibre-type distribution could potentially explain  
23 differences in normalized peak torque. However, previous studies have demonstrated no age

1 difference in fibre-type distribution between children and adults (Dubowitz 1965). Thus, the  
2 boys' lower peak torque should, at least in part, be explained by their lower rate of muscle  
3 activation, as reflected by the lower Q<sub>30</sub> observed in the present study, and by a lower extent of  
4 motor unit recruitment, as suggested previously (Belanger and McComas 1989; Falk et al.  
5 2009b; Halin et al. 2003; Paasuke et al. 2000).

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

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

20 The boys' lower absolute RTD is partly explained by its dependency on peak torque.  
21 Thus, normalizing RTD for peak torque can be useful in searching for more fundamental RTD-  
22 determining factors (Holtermann et al. 2007). The only two studies to have normalized children's  
23 RTD to peak torque, similarly reported lower RTD values in boys during elbow flexion and

1 extension compared with men (Asai and Aoki 1996; Falk et al. 2009b). Children's lower RTD  
2 then is a persistent finding, independent of their lower maximal strength or tested muscle group.  
3 These results suggest that other factors, such as lower rate of muscle activation or firing rate  
4 (Van Cutsem et al. 1998), are likely involved in determining children's RTD.

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

12 Shorter EMD reflects greater muscle-tendon stiffness, excitation-contraction coupling,  
13 and muscle-fibre conduction velocity (Cavanagh and Komi 1979; Halin et al. 2003). Compared  
14 with the men, our boys had longer EMD. Comparable age-related EMD difference has been  
15 reported earlier in elbow flexion (Asai and Aoki 1996; Falk et al. 2009b), elbow extension (Falk  
16 et al. 2009b), and plantar-flexion twitch contraction (Grosset et al. 2005). While no age-related  
17 differences in muscle-tendon stiffness was reported in elbow flexion (Cornu and Goubel 2001),  
18 others reported lower stiffness in boys during dorsiflexion (Lambertz et al. 2003). Thus, the  
19 boys' longer EMD may be attributed to their lower musculo-tendinous stiffness (Lambertz et al.  
20 2003) and to lower muscle activation or muscle fibre conduction velocity in boys (Halin et al.  
21 2003).

22 Grosset et al. (Grosset et al. 2009) found EMD to be significantly shorter after ten weeks  
23 of endurance training in men. While the EMD difference in the present study was not significant,

1 there was a trend for shorter EMD in the trained subjects ( $p=0.069$ ). Tendon stiffness was  
2 previously reported to increase after endurance training (Buchanan and Marsh 2001), and the  
3 muscle-tendon complex was found to be less compliant in long-distance runners than in  
4 untrained individuals (Kubo et al. 2000). Although it was suggested that EMD is highly  
5 dependent on the muscle-tendon stiffness (Cavanagh and Komi 1979), Grosset et al. (Grosset et  
6 al. 2009) found musculo-tendinous stiffness changes to account for only 20% of the variance in  
7 training-induced EMD changes. Thus, the rate of muscle activation and the type of recruited  
8 MUs could not be ruled out as likely contributors to EMD and changes thereof.

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

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

11           In summary, during maximal voluntary isometric muscle contractions men were stronger,  
12 had higher RTD and  $Q_{30}$  than the boys, in both absolute and size-normalized values, and had  
13 shorter EMD and time-to-peak RTD. Endurance-training could only be shown to have affected a  
14 higher  $Q_{30}$  in the men with no corresponding performance differences in any of the measured  
15 variables. Thus,  $Q_{30}$ 's functional and discriminatory significance is unclear, at least in as much as  
16 endurance training is concerned. It thus appears that the functional effects of endurance training  
17 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<sub>30</sub>) in the endurance-trained and untrained boys and men. A. Q<sub>30</sub> in absolute values, B. Q<sub>30</sub> 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<sub>30</sub> 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.

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Figure 1

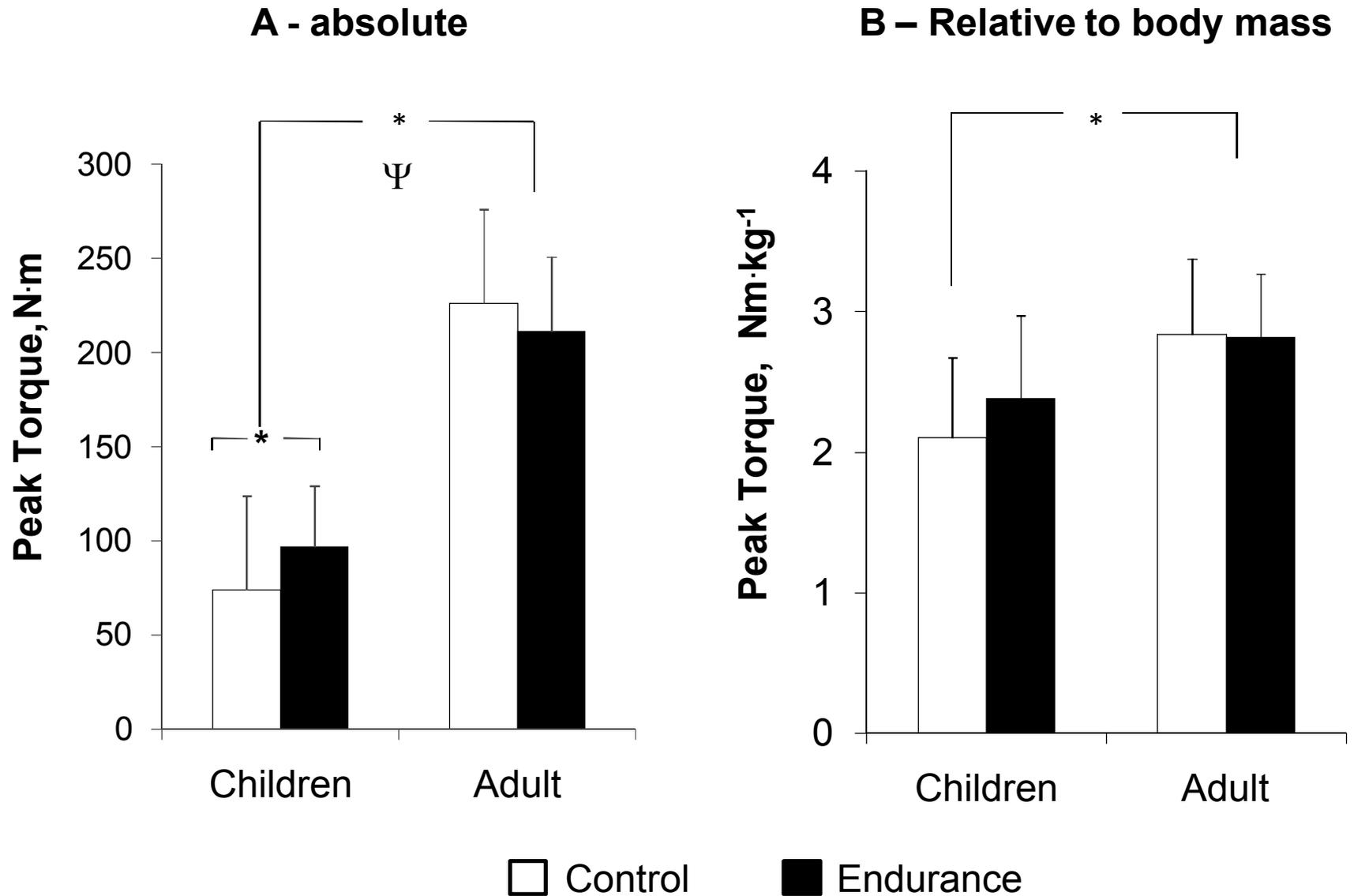


Figure 2

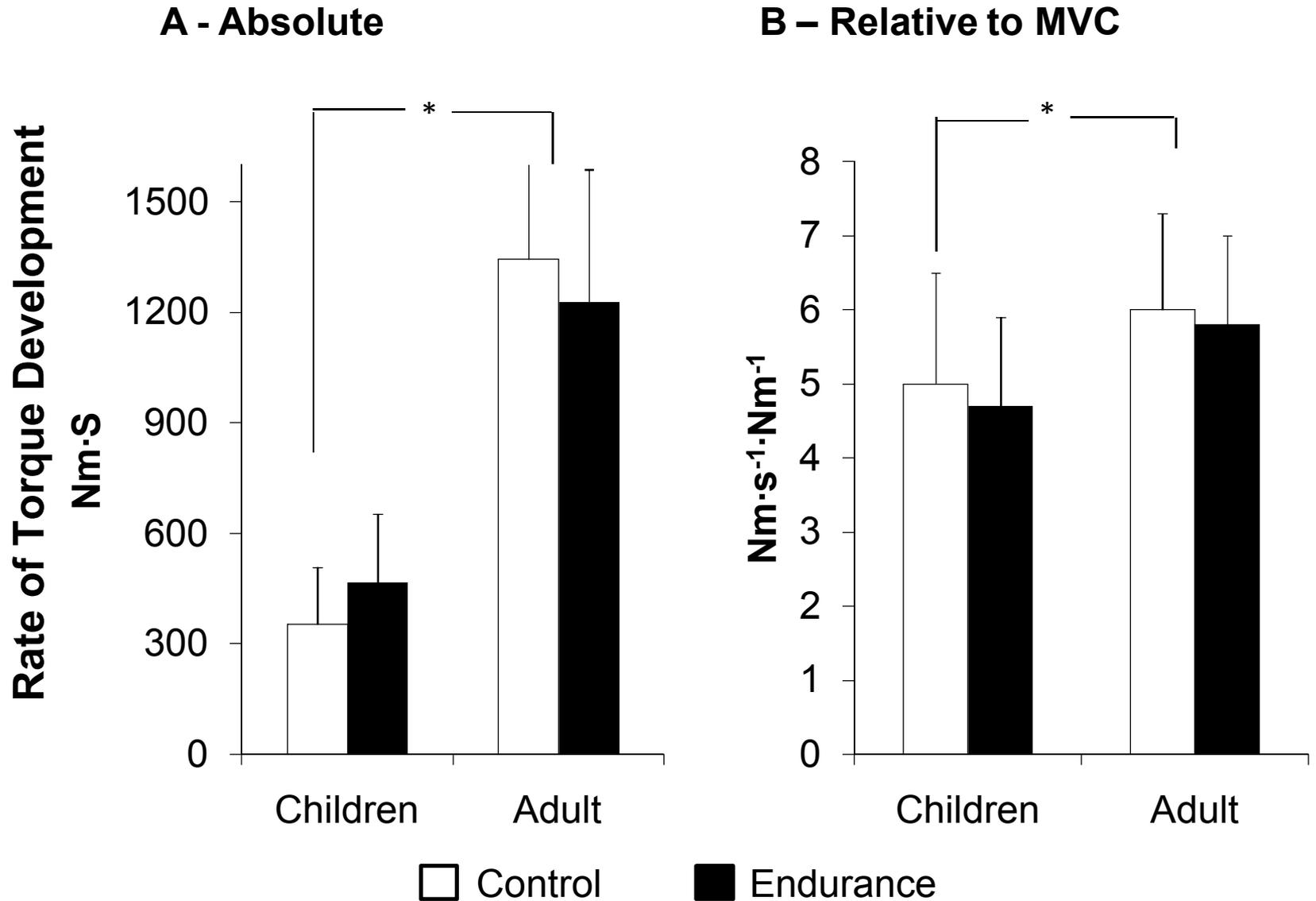


Figure 3

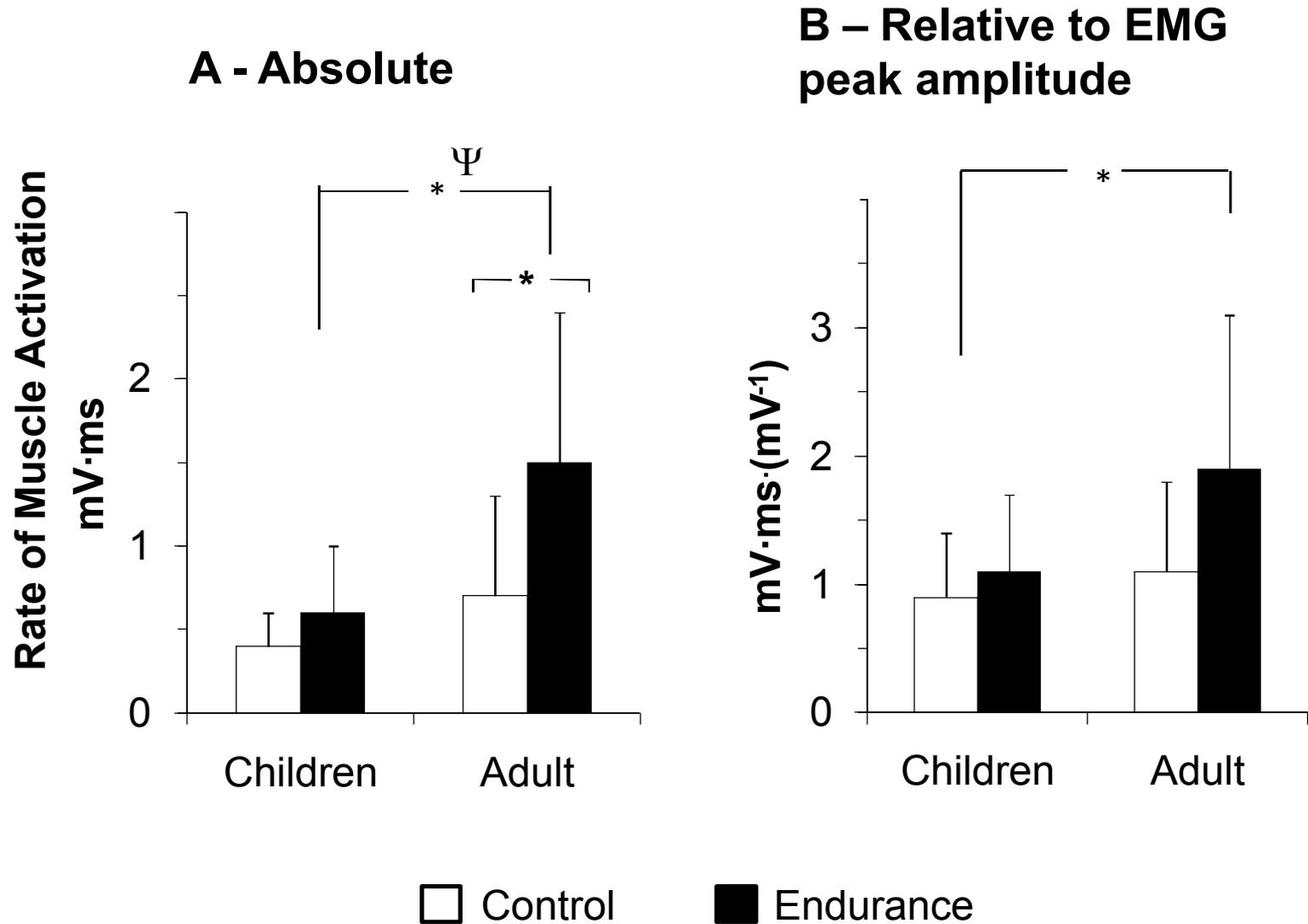


Figure 4

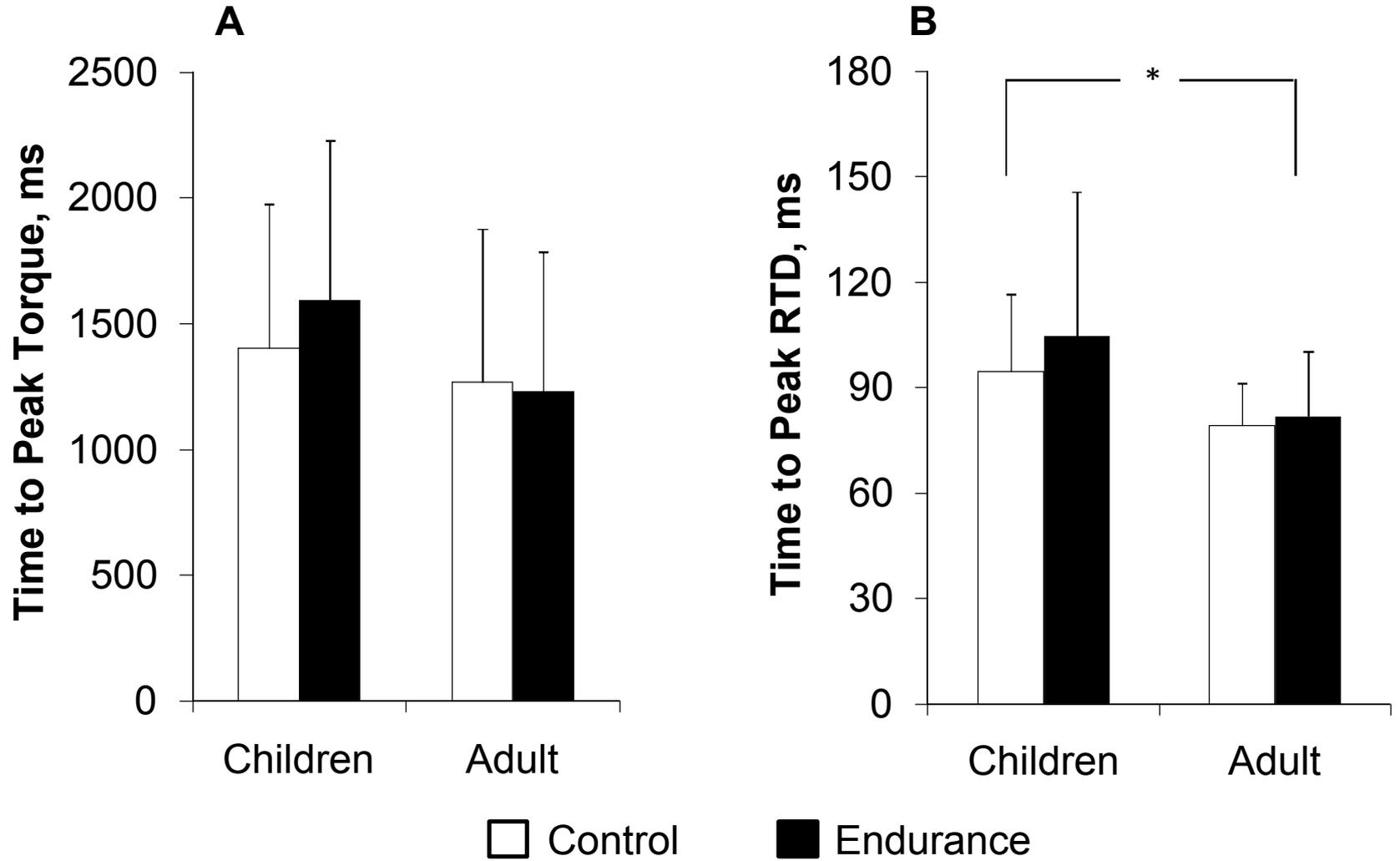
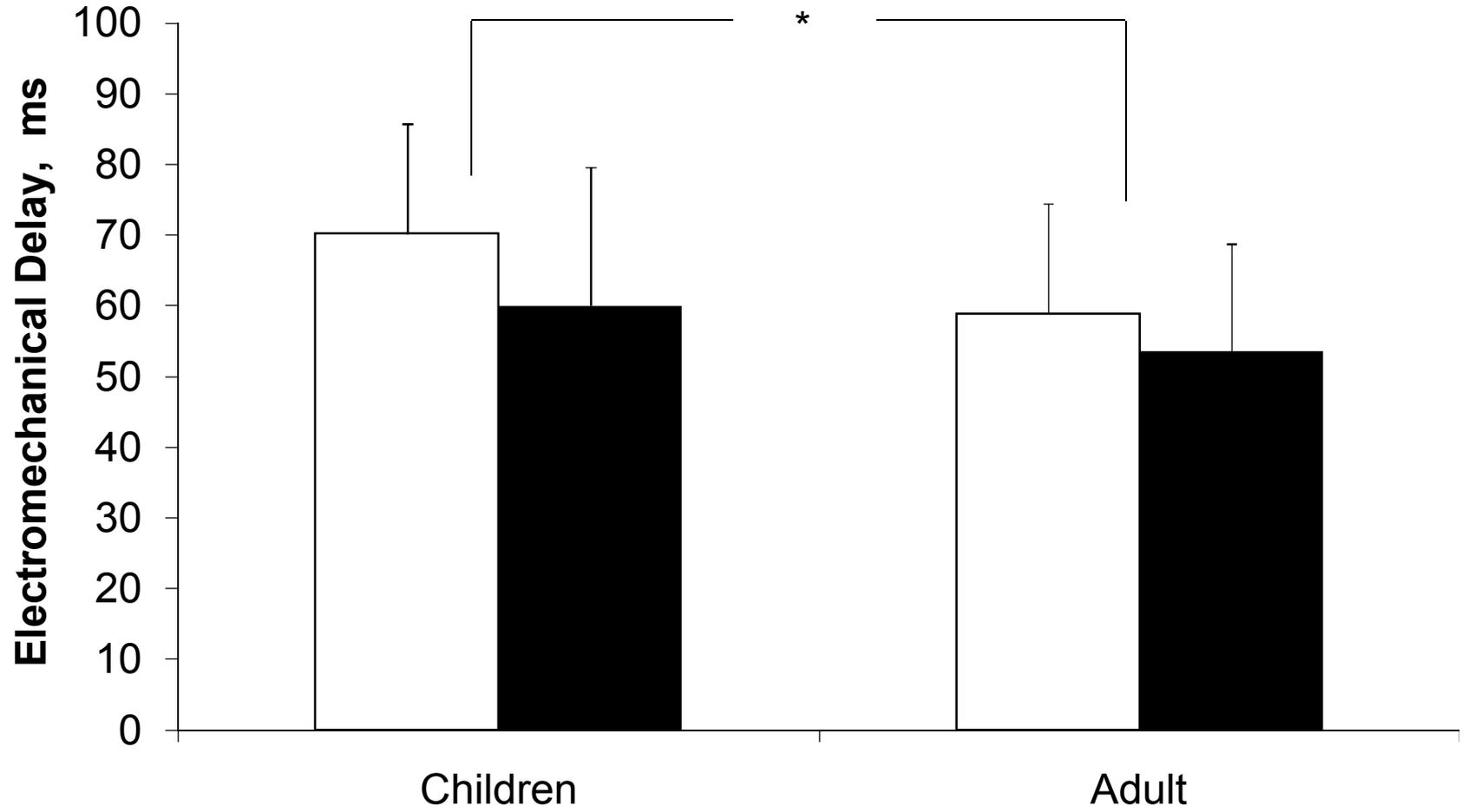


Figure 5

□ Control      ■ Endurance



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

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

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

	<b>Age effect</b>	<b>Training effect</b>	<b>Age*training interaction</b>
<b>Torque:</b> Absolute	<0.001	-	0.030
Per Kg	<0.001	-	-
<b>RTD:</b> Absolute	<0.001	-	-
Per torque	<0.001	-	-
<b>Q<sub>30</sub>:</b> Absolute	<0.001	-	-
Per EMG <sub>amp</sub>	<0.001	-	0.032
<b>T to peak torque</b>	0.002	-	-
<b>T to peak RFD</b>	<0.001	-	-
<b>EMD</b>	<0.001	-	-
<b>Co-activation</b>	0.013	0.031	-