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ORIGINAL ARTICLE

Prepubescent males are less susceptible to neuromuscular fatigue following resistance exercise

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Abstract

Purpose To determine if prepubescent and adult males have similar fatigue profiles following high and lower intensity knee extensions.

Methods Ten male children and ten adults completed two sessions of three sets of high repetition (17 typical muscle endurance training) high repetition (High RM) or low repetition (seven typical strength training) maximum (Low RM) dynamic knee extensions. Voluntary and evoked contractile properties, heart rate (HR), and rating of perceived exertion (RPE) were assessed before and after each knee extension RM.

Results Knee extension RM measures revealed that boys performed more (children set 2, 6.7 ± 0.5; set 3, 5.7 ± 0.5 vs. adult set 2, 5.2 ± 0.4; set 3, 3.5 ± 0.5; $P < 0.001$) repetitions, had a faster (children 39.9 ± 8.6 vs. adult 9.4 ± 3.7 bpm; $P < 0.001$) HR recovery and lower (6.4 ± 0.43; $P < 0.001$) RPE compared to adults (8.0 ± 0.4). Post-knee extension measures also revealed a smaller MVC force decrement ($P < 0.001$) with boys (94.3 % ±6.1 vs. 76.3 % ±4.1). Unlike adults, there were no significant decrements to children's evoked contractile properties or EMG. The greater boys' antagonist activation (children 125.7 % ±9.2 vs. adult: 103.5 % ±6.7; $P < 0.001$) post-knee extension would suggest muscle coordination changes as a primary mechanism for MVC force decrements. The lower RPE and similar agonist EMG activity may also indicate an inability of boys to perceive or produce a maximal effort.

Conclusion Independent of High or Low RM knee extensions, boys had greater neuromuscular fatigue resistance and recovered faster than adults.

Keywords Children · Recovery · EMG · Evoked contractile properties · Rating of perceived exertion

Introduction

Fatigue associated with repeated or sustained high-intensity muscle contractions has been defined as a transient decrease in working capacity (Asmussen and Mazin 1978), force output (Fitts and Metzger 1993), or muscle force generating capacity (Degens and Veerkamp 1994). However, fatigue can also been defined as an increase in the perceived effort needed to exert a desired force (Enoka and Stuart 1992). The extent of fatigue-related force decrements and perception of fatigue sustained by children may not always parallel that of adults (Behm et al. 2008; Falk and Dotan 2006).

Although exercise guidelines for children address the duration, intensity and frequency of exercise (Faigenbaum et al. 2008, 2009), recovery intervals for children following resistance exercise are not well established. In contrast to the dearth of information regarding recovery intervals in children, research on adult recovery intervals and resistance exercise-induced fatigue (Barry and Enoka 2007; Behm et al. 2002a; Behm and StPierre 1997) is extensive.

The identification of exercise-induced fatigue mechanisms has promoted the development of various adult

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training parameters, including recovery intervals. Children have been shown to recover quicker than adults and therefore the same training principles may not apply (Falk and Dotan 2006; Ratel et al. 2006). Some of the factors attributed to the quicker recovery in children are a lower reliance on glycolysis (Zafeiridis et al. 2005), quicker phosphocreatine resynthesis (Taylor et al. 1997), faster acid base regulation (Ratel et al. 2002), and increased fatigue resistance due to a lower power output (Falk and Dotan 2006). Despite the information available on mechanisms related to children's more rapid recovery, there is still little known about neuromuscular mechanisms with respect to exercise-induced fatigue with children. Few studies have attempted to address the relationship between recovery intervals and neuromuscular mechanisms with children. Secondly, almost all children recovery interval studies have used either isometric (Armatas et al. 2010) or isokinetic (Zafeiridis et al. 2005) contractions and with only one study using isotonic contractions, which are most predominant in activities of daily living. The only study to use isotonic contractions did report quicker recovery of children when compared to adolescents and adults following recovery intervals as low as 1 min. However, none of the associated mechanisms were reported (Faigenbaum et al. 2008).

Based on the few previous studies comparing adults to children (Behm et al. 2008), it is still unknown whether children respond differently to high (endurance) and low (strength) number of repetitions following similar recovery intervals. Although children have been shown to recover quicker than adults, no studies have used dynamic resistance exercise with different repetition protocols to examine this phenomenon. Also, neuromuscular mechanisms relating to exercise-induced fatigue and the more rapid recovery with children are limited.

The objective of this study was to examine perceptual [rating of perceived exertion (RPE)], voluntary and evoked contractile properties indices of fatigue and recovery in prepubescent and adult males with high (representative of muscle endurance training) and low (representative of strength training) number of dynamic quadriceps contractions. It was hypothesized that despite the difference in repetitions, the prepubescent boys would (a) respond similarly for both conditions, (b) show less neuromuscular fatigue than adults under both conditions and thus (c) recover faster.

Methods

Participants

Ten prepubescent males (9.7 ± 0.94 years; 104.2 ± 2.8 cm; 36.6 ± 3.2 kg) and ten adult males (25.7 ± 2.4 years; 179.3 ± 3.6 cm; 82.7 ± 6.5 kg) participated in this study. Prepubescent and adult participants were recruited from youth athletic associations (hockey, soccer, and kickboxing) and the university population (Memorial University of Newfoundland, St. Johns, N.L.), respectively. Youth participants were classified as competitive athletes as they trained on a regular basis (3–5 days per week) for their competition based sports. Testing occurred within the children's competitive season. Adult participants had a history of participating in competitive sports, however, all were currently recreational athletes. Thorough explanation of the procedures, risks, and benefits of the study were given and written informed consent was obtained from the men, boys' parents, and boys. Modified physical activity readiness questionnaires (PAR-Q) were also signed prior to participation (Hommerding et al. 2010). Maturation status for prepubescent boys was determined by a self-assessment questionnaire in which participants assessed their genital and pubic hair development according to the criteria of Tanner and Whitehouse (1976). This questionnaire has been used in a number of other child training studies (Chaouachi et al. 2008, 2011). All child participants rated themselves at Tanner level 1, representative of pre-pubescence. This study was granted ethical approval by Memorial University's Human Investigations Committee.

Experimental procedures

In an attempt to induce fatigue, participants completed two randomized experimental sessions, which included either three sets of high repetition maximum (High RM) or low repetition maximum (Low RM), knee extensions (tempo of 1 s concentric and 1 s eccentric contraction controlled by a metronome) with a 1-min rest interval between sets. There was approximately 48 h between each experimental session and each subject was tested at similar times to ensure differences in diurnal rhythms did not affect the results (Paddock and Behm 2009). Participants were given instructions to refrain from any high-intensity exercise 48 h prior to each session and were asked to restrict any food intake up to 3 h before testing. All sessions (orientation and experimental) were approximately 1 h in duration (Fig. 1).

Prior to the start of experimental sessions, all participants were given two orientation sessions held on non-consecutive days to allow for familiarization of the equipment being used in the experimental sessions and to determine RM for High RM and Low RM. RM were determined using a Cybex isotonic leg extension machine and followed the procedure for RM testing outlined by Baechle and Earle (2008) for adults and the methods of Faigenbaum et al. (2003) for children. To determine appropriate repetition number, resistance levels were progressively adjusted to achieve two different repetition ranges of 5–10 and 15–20

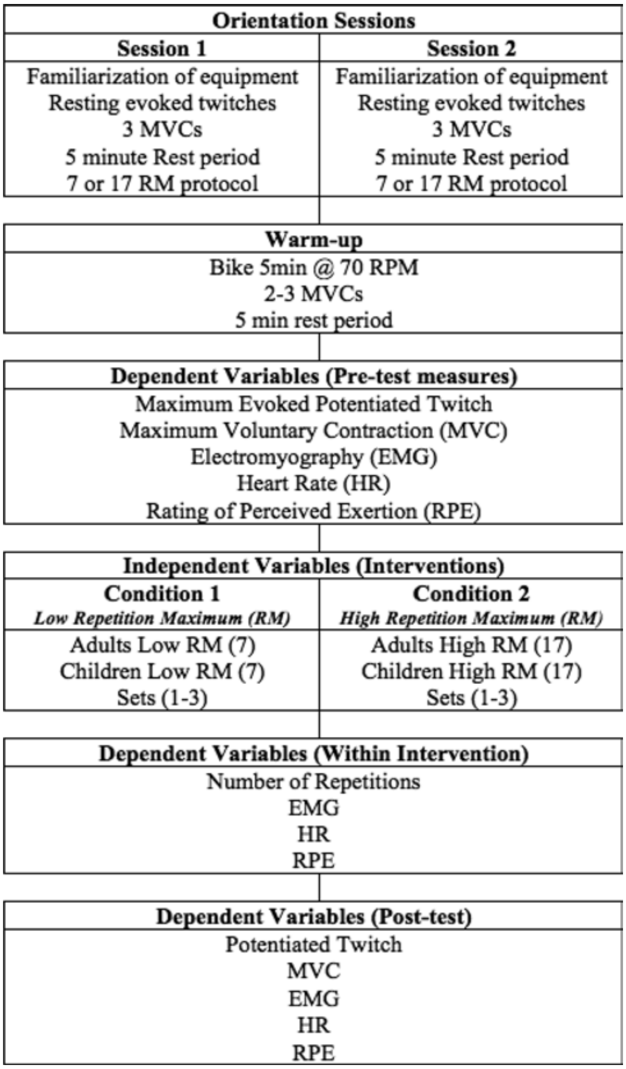

Fig. 1 Experimental design

during pilot testing. Results showed that average repetition number amongst participants during the knee extension for the Low RM and High RM were 7 and 17, respectively. The average RMs (7 and 17) for Low RM and High RM were chosen to represent the possible fatiguing effects of strength/hypertrophy and endurance resistance training, respectively. According to the American College of Sports Medicine Position stand, these average repetition numbers represent for adults and children approximately >80 % (7 RM) to 60 % (17 RM) of 1 RM (ACSM 2014). However, there is less research available for children on relative intensities of repetition numbers and thus these percentages should be taken as a broad estimate.

At the beginning of each session, a maximum evoked twitch was determined for the measurement of evoked contractile properties during the rest of the session. As a standard warm-up, participants were asked to perform two submaximal contractions at approximately 50 % of maximum intensity, 2–3 maximal voluntary contractions (MVC) followed by 5 min of pedaling on a Monark cycle ergometer. Adults were instructed to pedal at 1 kp and 70 rpm (70 W), whereas children were required to select a comfortable resistance and cadence, but not to exceed the adult standard (Armatas et al. 2010). Following the warm-up, participants were given a 5-min recovery to allow for heart rate (HR) to return to baseline. Pre- and post-knee extension RM measures included an evoked resting twitch, MVC, and potentiated twitch. Participants rested another 5 min before knee extension RM began. Following the knee extension RM, participants were positioned on the isometric leg extension chair to perform post-knee extension RM measures. Throughout the experimental session, HR was monitored using Polar heart rate monitor (Woodbury, NY), and RM were recorded during each set.

Testing apparatus

The study was conducted with participants seated in a straight back isometric leg extension chair and on a Cybex leg extension machine that allowed for both their hips and knees to be flexed at 90° (fully extended leg was set as 0°). As there is no difference reported in knee joint angle at which peak knee extension moment occurs between children and adults, both groups were positioned in the same manner to allow for identical knee joint angles (O'Brien et al. 2009). To measure quadriceps force production in the isometric chair, a reinforced strap was placed around the ankle, attached by a high-tension wire to a Wheatstone bridge configuration strain gauge (Omega Engineering Inc., Don Mills, Ont.). The height of the strain gauge was adjusted to ensure it was always perpendicular to the lower limb of each subject. Leg extension force was measured through a strain gauge, amplified (DA 100 and analog-to-digital converter MP150 WSW, Biopac Systems Inc., Holliston, Mass), and monitored on a computer. All data were collected at 2,000 Hz. The subject's body was secured in the chair via straps around chest and dominant leg. Dominance was determined from the leg used to kick a soccer ball and one-legged jump preference.

Electromyography

The biarticular rectus femoris (RF) and biceps femoris (BF) were monitored for EMG activity. Electrode placement for the agonist RF muscle was determined from the midpoint between the anterior superior iliac spine to the apex of the patella. Antagonist BF electrode placement was determined on the posterior thigh at the midpoint between the ischial tuberosity and the posterior aspect of the lateral epicondyle of the femur. Skin preparation for all electrodes included shaving the area of interest (using a sterile razor), followed by removal of dead epithelial cells with a piece of sandpaper, and cleansing with isopropyl rubbing alcohol (70 %). A ground electrode was placed on the proximal head of the fibula. EMG activity was measured during evoked and voluntary contractions (isometric and dynamic). The EMG signal was sampled at 2,000 Hz, with a Blackman—61 dB band-pass filter between 10 and 500 Hz, amplified (bipolar differential amplifier; input impedance =2 MO; common mode rejection ratio >110 dB min (50/60 Hz); gain 1,000; noise >5 mV), and analog-to-digitally converted (Biopac MP150) and stored on a personal computer for further analysis. During all MVCs, EMG analysis of RF and BF included the mean amplitude of the root mean square (rms) EMG signal during a 500-ms interval during the maximal force output. All results were normalized to pre-knee extension RM values.

For all dynamic knee extensions, EMG analysis was performed similarly to the MVC EMG, except the analysis occurred during a 500 ms interval taken from the middle of the concentric component. The mean amplitude of the rms EMG signal during the first two (early) and last two (late) repetitions were normalized to the MVC and compared.

During pre-and post-knee extension RM measures, muscle action potential wave (M-wave) amplitudes were recorded. For comparison purposes between the children and adults, all post-knee extension RM values were normalized as a percentage of pre-knee extension RM values.

Evoked contractile properties

Measurements for stimulating electrode placement were established over the inguinal region and just superior to the apex of the patella. The stimulating electrodes were constructed in the laboratory from aluminum foil (approximately 10–12 cm by 3–4 cm) and were coated with a conducting gel (EcoGel 200; multipurpose ultrasound gel). Electrodes were then wrapped in paper towel and soaked in an aqueous solution. Electrode position was maintained between sessions by outlining the electrode position with ink. The amperage (maximum 1 A) and voltage (maximum 400 V) of the stimulation (Digitimer Stimulator, Model DS7H+ , Welwyn Garden City, Hertfordshire, UK) were both progressively increased until reaching a maximum twitch force plateau. Pulse duration was maintained at 50 µs. Using the same acquisition hardware, software, procedures, and body positioning as the voluntary force measures, isometric leg extension force was measured. Potentiated twitches were conducted 5 s following each MVC. For each twitch, half relaxation time (½ RT) was calculated as the time period for the peak twitch force to decrease to 50 % of the peak twitch force. The time to peak twitch (TPT) was measured as the time period of the peak-to-peak value from baseline to the peak twitch force. Electromechanical delay was measured using the methods (onset of M-wave to onset of force production) of Grosset et al. (2005). Similar to previous measures, all evoked contractile properties recorded post-knee extension RM were normalized as a percentage of their corresponding pre-knee extension RM values for comparison between children and adults.

Maximal voluntary and dynamic contractions

During the warm-up, participants performed two submaximal contractions (participants were encouraged to contract at around 50 % of a MVC). Following the submaximal contractions, 2 min of rest was given and participants were then instructed to complete two MVCs with a recovery interval of 2 min. Verbal instructions to maximally contract the quadriceps as hard and fast as possible were given to each subject prior to each MVC. The subject's hands were placed on railings beside their thighs, and the ankle was placed in a padded strap and the cable was maintained in a taut position to help prevent movement of the knee joint during the data collection. Verbal motivation was given by the investigator during the contraction to promote a maximal response. Each contraction lasted for 5 s. Peak force was measured and if there was a >5 % difference between the first two MVC trials, the subject was asked to perform a third trial, separated by 2 min, and the highest MVC force was recorded. The warm-up was concluded with 2 min of rest and instruction on the upcoming procedures. During the pre- and post-knee extension RM measures, MVCs were conducted and recorded in the same manner as describe for the warm-up, but only one MVC was performed.

During knee extensions, participants were monitored and verbally encouraged for each set. The total number of repetitions was determined using a potentiometer to measure knee joint angles. Failure to meet the cutoff criteria of 75^{o} (approximately 20 % decrease in the range of motion) or greater would eliminate the repetition from being counted.

Heart rate and rate of perceived exertion

Heart rate was monitored using a Polar™ HR monitor (Woodbury NY), and recorded throughout each experimental session. Specifically, HR was recorded before and after warm-up, after each exercise set, and at the end of each corresponding recovery phase. RPE was determined immediately after the warm-up, and after each exercise set using the Children's Effort Rating Table (Williams et al. 1994). The sensations corresponding to each value of the scale were explained to each subject before the test. To determine the efficiency of HR recovery, the analysis of HR includes the difference between post-knee extension RM recovery HR and pre-knee extension RM resting HR. Reference to this analysis is referred to as delta HR (ΔHR).

Statistical analysis

A three-way ANOVA with repeated measures was performed on all dependent variables (SPSS 18.0 for Macintosh, IBM Corporation, Armonk, New York, USA). The three factors included time (pre- and post-knee extension RM), group (children and adults), and repetitions (Low RM and High RM). Another three-way ANOVA with repeated measures was also performed on all dependent variables recorded during the experimental session. The three factors included sets (1, 2, and 3), group (children and adults), and repetitions (Low RM and High RM). F ratios were considered significant at $P < 0.05$. A Bonferroni correction was applied for multiple planned contrasts to test for significant differences between interactions. Descriptive statistics include mean ± standard deviation (SD) for both the text and figures.

Results

Between and within group voluntary measures results for sets (1, 2, 3), group (children and adults) and repetitions (High RM and Low RM)

Within set repetitions During the High RM sets, the children performed 21.6 and 35.9 % more repetitions than adults in sets 2 and 3, respectively (Fig. 2a). Similarly, during the Low RM sets, children performed 21.4 and 31.4 % more repetitions than adults in sets 2 and 3, respectively ($P < 0.001$) (Fig. 2b).

Children had a significant decrease of 13.7 % in set 3 when compared to set 1 for the High RM sets ($P < 0.01$). In the High RM sets, adults had a significant decrease in repetitions by 36.2 and 46.5 % for sets 2 and 3 when compared to set 1, respectively ($P < 0.001$). A similar effect was found for adults during the Low RM sets, which included a significant decrease in repetitions by 37.2 and 41.1 % for sets 2 and 3 when compared to set 1, respectively ($P < 0.001$). Repetitions in sets 3 were also found to be 17.4 and 16.1 % significantly lower when compared to set 2 for adults during Low RM and High RM sets, respectively ($P < 0.01$).

Electromyography (EMG) during the resistance exercise Children had 56.6 and 34.6 % greater RF activity than adults during the beginning and end of the High RM sets (Fig. 3a), as well as 45.7 and 31.2 % greater RF activity than adults at the beginning and end of the Low RM sets (Fig. 3b), respectively ($P < 0.005$).

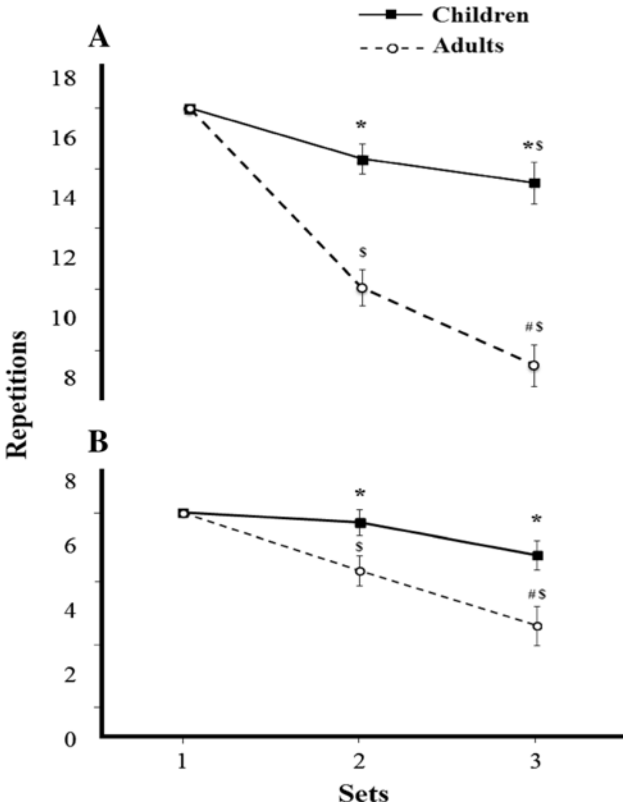

Fig. 2 Repetition performance. **a** Represents differences in repetition performance during a High repetition maximum (High RM) protocol between children and adults as well as individual group performance each set. **b** Represents differences in repetition performance during a Low repetition maximum (Low RM) protocol between children and adults as well as individual group performance each set. In **a** and **b**, *solid colored squares* and *opened face circles* represent means and standard deviations for children and adults, respectively. *Asterisk* indicates statistically significant differences ($P < 0.05$) from adults. *Dollar sign* indicates a statistically significant difference ($P < 0.05$) from set 1 within groups, whereas a *number sign* indicates a statistically significant difference from set 2

Adults showed a significant ($P < 0.01$) increase of 22.1 and 28.4 % in RF at the end of the Low RM and High RM sets when compared to the beginning of each set, respectively, whereas there was no change in EMG for children.

Heart rate

Delta HR (recovery–resting) The Low RM and High RM exercises resulted in 30.5 and 28.9 beats/min lower HR difference for children when compared to adults, respectively ($P < 0.001$) (Fig. 4a). Children also had 28.5, 30.4 and 30.3 beats/min less difference when compared to adults for sets 1, 2, and 3, respectively ($P < 0.001$) (Fig. 4b). A main effect for group was found with children having a smaller difference (9.1 beats/min) in recovery and resting HR than adults (38.8 beats/min) ($P < 0.001$).

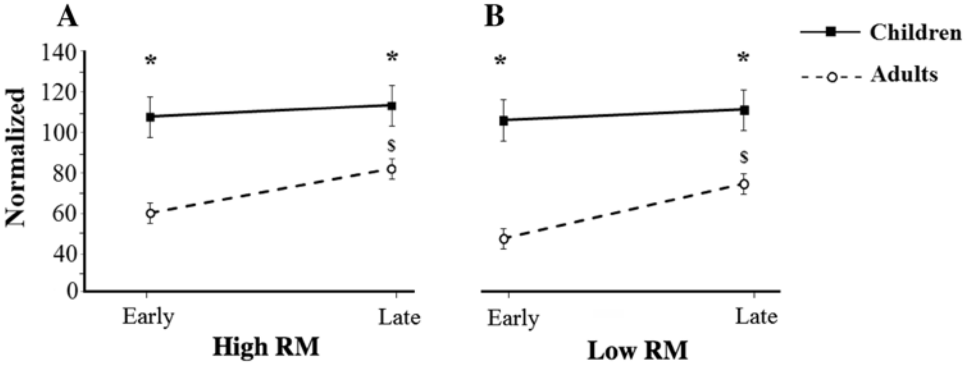

Fig. 3 Normalized EMG during repetitions. **a** Represent differences in normalized rectus femoris EMG activity for early and late repetitions during a high repetition maximum (High RM) protocol for children and adults. **b** Represent differences in normalized rectus femoris EMG activity for early and late repetitions during a low repetition maximum (Low RM) protocol for children and adults. In **a** and **b**, *solid colored squares* and *opened face circles* represent means and standard deviations for children and adults, respectively. *Asterisk* indicates statistically significant differences ($P < 0.05$) from adults. A *dollar sign* indicates a statistically significant difference ($P < 0.05$) from early rectus femoris EMG activity within group

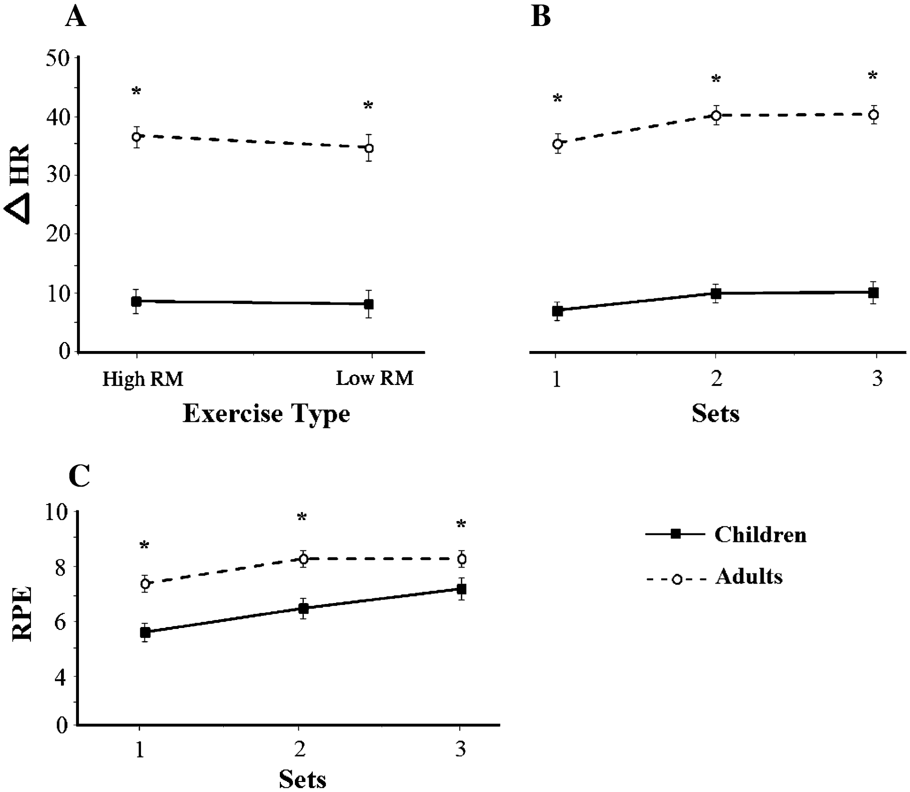

Fig. 4 HR and RPE during repetitions. **a** Represent differences in the change in heart rate (ΔHR) between children and adults during high (High RM) and low repetition maximum (Low RM) protocols. **b** Represent differences in the change in heart rate (ΔHR) between children and adults during each set of the knee extension RM protocols. **c** Represent differences in rate of perceived exertion (ΔHR) between children and adults during each set of the knee extension RM protocols. In **a**–**c**, *solid colored squares* and *opened face circles* represent means and standard deviations for children and adults, respectively. *Asterisk* indicates statistically significant differences ($P < 0.05$) from adults

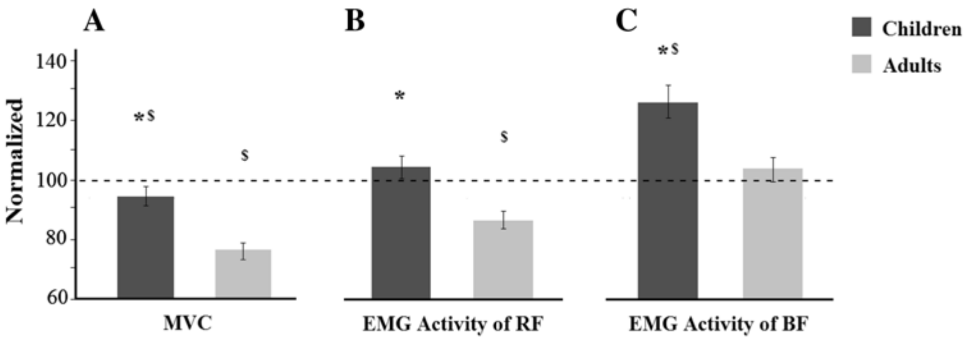

Fig. 5 Maximum voluntary contractions. **a** Represent differences in post-knee extension RM maximum voluntary contraction (MVC) force between children and adults as well as differences from pre-knee extension RM values. **b** Represent differences in post-knee extension RM rectus femoris (RF) EMG activity between children and adults as well as differences from pre-knee extension RM values. **c** Represent differences in post-knee extension RM biceps femoris (BF) EMG activity between children and adults as well as differences from pre-knee extension RM values. In **a**–**c**, *dark and light colored columns* represent means and standard deviation for children and adults respectively. *Dashed line* represents pre-knee extension RM values. *Single asterisk* indicates statistically significant differences ($P < 0.05$) from adults, whereas a *dollar sign* indicates a statistically significant difference ($P < 0.05$) from pre-knee extension RM values

Rating of perceived exertion

RPE Children were found to have 17.5, 17.5, and 11.5 % lower RPE than adults in sets 1, 2, and 3, respectively ($P < 0.001$) (Fig. 4c). RPE scores for children were 16.5 and 7 % greater in set 3 when compared to sets 1 ($P < 0.001$) and 2 ($P < 0.001$), respectively.

Between group voluntary measures results for time (pre- and post-test), group (children and adults) and repetitions (High RM and Low RM)

Maximal voluntary contraction (MVC) Post-knee extension RM measures showed a greater decrease ($P < 0.001$) in percentage of MVC following the sets for adults (23.7 %) when compared to children (5.7 %) (Fig. 5a). A main effect for group was found with children performing a greater percentage of their MVC, 97.4 vs. 88.1 %, over adults, respectively ($P < 0.001$).

Pre- and post-knee extension RM MVC electromyography (EMG) During the 1-min post-knee extension RM measures, children showed 17.9 and 22.2 % greater RF ($P < 0.001$) (Fig. 5b) and BF activity ($P < 0.001$), respectively, when compared to adults (Fig. 5c). Compared to pre-knee extension RM measures, adults showed a significant ($P < 0.001$) decrease of 15.2 % in post-knee extension RM RF activation. Children showed a significant ($P < 0.001$) increase of 20.6 % in post-knee extension RM BF activation. A main effect for group was found with children showing 9 and 11.2 % increases in RF ($P < 0.001$) and BF ($P < 0.001$) EMG activity, respectively, compared to adults.

Evoked contractile properties

Peak twitch force During post-knee extension RMs, children's potentiated twitch was 10.7 % greater than adults ($P < 0.05$). Post-knee extension RM potentiated twitch results for children were found to be 4.5 % ($P < 0.05$) greater than pre-knee extension RM results, whereas in contrast, adults were 6.2 % ($P < 0.05$) lower (Fig. 6a). A main effect for group was found with children showing a twitch force, relative to pre-test, of 4.7 % greater than adults ($P < 0.05$). There were no significant findings for TPT and electromechanical delay.

Half relaxation time (½ RT) Compared to pre-knee extension RM measures, adults ½ RT measures significantly ($P < 0.001$) increased by 24.1 %, whereas children's ½ RT did not change (3.1 %). Adult's post-knee extension RM ½ RT were also significantly higher than the children (Fig. 6b).

Muscle action potential wave (M-wave) amplitude Post-knee extension RM M-wave amplitudes for children were 5.8 % ($P < 0.01$) greater than adults (Fig. 6c). Compared to pre-knee extension RM values, post-knee extension RM M-wave amplitudes were 2.6 % ($P < 0.05$) greater for children, contrasting with a 3.5 % ($P < 0.05$) decrease for adults.

Discussion

The most significant findings of this study were that prepubescent males exhibited less fatigue with three sets of resistance exercise and recovered more rapidly than adults. Furthermore, rather than exhibiting the typical

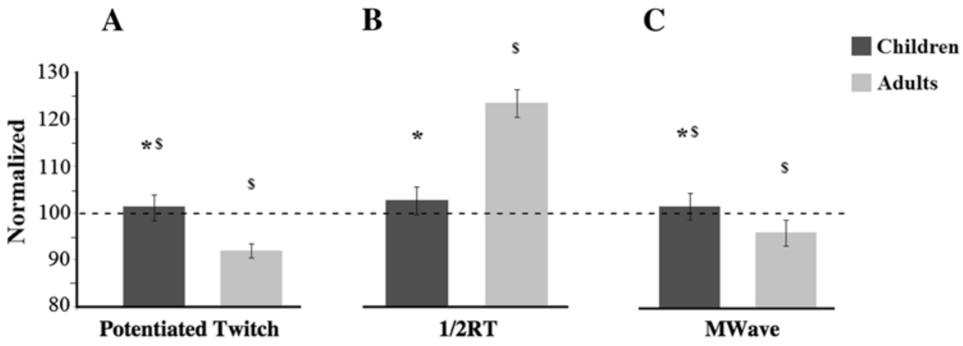

Fig. 6 Evoked contractile properties. **a** Represent differences in post-knee extension RM potentiated peak twitch between children and adults as well as differences from pre-knee extension RM values. **b** Represent differences in post-knee extension RM half relaxation time (½ RT) between children and adults as well as differences from pre-knee extension RM values. **c** Represent differences in post-knee extension RM muscle action potential wave (M-Wave) between children and adults as well as differences from pre-knee extension RM values. In **a**–**c**, *dark and light colored columns* represent means and standard deviation for children and adults, respectively. *Dashed line* represents pre-knee extension RM values. *Single asterisk* indicates statistically significant differences ($P < 0.05$) from adults, whereas a *dollar sign* indicates a statistically significant difference ($P < 0.05$) from pre-knee extension RM values

adult response of a reduction in EMG activity with fatigue involving high-intensity contractions as exemplified by the adults in the present study, the children responded with higher muscle activity following the completion of the three sets of leg extensions. This lack of neural activation mediated fatigue was accompanied by a lack of peripheral fatigue as evidenced by no significant changes in children's quadriceps' evoked contractile properties. Hence, the fatigue associated with the children was related more to an increased antagonist activity (changes in motor control) than with adults.

In accordance with Falk and Dotan (2006), children in this study may not have fatigued to a significant extent due to an inability to provide a maximal exertion. The supposition that the children were unable to produce a maximal contraction was based on the significantly lower fatigue when compared to adults, the potentiation of twitch force and lack of changes in TPT and electromechanical delay post-fatigue. In adults, EMG activity typically declines with fatiguing maximal or near maximal intensity contractions (Armatas et al. 2010; Vollestad 1997). The possibility that maximal or near maximal activation was not achieved with the children is in accordance with much of the pediatric literature which supports the notion that full activation may be compromised with younger populations (Falk and Dotan 2006; Ratel et al. 2006). It is not known from the results of the present study whether this possible inability to provide a maximal exertion can be attributed to a lack of experience or exposure to this contraction intensity or whether the children were neurologically immature.

However, it should be noted that some researchers have reported complete activation in children. Belanger and McComas (1989) found that eight of the ten children tested were able to fully activate their plantar flexors. One possible argument for this discrepancy might be the use of plantar flexors, whereas muscle activation has been shown to differ amongst different muscle groups (Behm et al. 2002b). In adults, the quadriceps have been shown to be more difficult to fully activate than the plantar flexors (Behm et al. 2002b). Also, the majority of the children in the Belanger and McComas (1989) study were older (12 and 13 years old) than the 8–11 year old children in the present study.

Agonist EMG activity remained relatively high for children following the exercise protocols, whereas it decreased significantly for adults. During repetitive submaximal contractions, adult EMG activity typically increases with fatigue (Vollestad 1997). The increased EMG with fatiguing submaximal contractions, reported in both adults (Behm 2004) and children (Hatzikotoulas et al. 2009) has been attributed to increases in motor unit recruitment, rate coding and synchronization (Behm 2004). To our knowledge, there have only been a few studies examining EMG activity with submaximal fatiguing exercise in children and adults (Bassa et al. 2005; Hatzikotoulas et al. 2009; Kotzamanidou et al. 2005; Moalla et al. 2006). The results of the present study are consistent with the literature (Armatas et al. 2010), that agonist activity for both children and adults during prolonged submaximal contractions increased, signifying that fatigue was present. However, in the present study children displayed similar EMG activity levels for both the low repetition (strength) and high repetition (endurance) protocols. Again this provides evidence that the children had difficulty perceiving the difference between maximal and submaximal intensity contractions.

The evoked twitch contractile properties and M-wave results also confirm low fatigue levels in children, and provide possible mechanisms as to why adults fatigue more.

Because both the twitch torque and M-wave amplitude during post-test measures were potentiated in children, there is reason to believe they did not succumb to the impairments related to increased glycolytic metabolism (Ratel et al. 2006). The depressed twitch force in adults indicates possible impairments with excitation contraction coupling process (Behm and StPierre 1997). Specifically, a depressed M-wave suggests failures in the muscle membrane action potential propagation (Place et al. 2007). However, there was no significant difference with adult TPT, but a significant increase in post-test ½ RT. Hence, an additional adult temporal fatigue component may be attributed to impairments in the rate of Ca^{2+} sequestering (Behm and StPierre 1997). As no significant differences were found with pre- and post- knee extension RM evoked contractile properties in children, there were likely no substantial peripheral fatigue mechanisms. This is the first study examining dynamic fatiguing contractions in children using evoked contractile properties. The notion that children rely less on glycolytic metabolism as a result of their fiber predominance (Behm et al. 2008; Ratel et al. 2006), suggests that it is plausible that peripheral mechanisms did not affect the fatigue processes in the children to an appreciable amount.

With respect to the potentiation observed in the children, it should be noted that both potentiation and fatigue can occur simultaneously, and thus it has been suggested that the results be interpreted carefully (Sale 2002). To our knowledge there is only one study that addresses potentiation and fatigue in children (Chaouachi et al. 2011). In accordance with our findings, Chaouachi et al. (2011) reported full recovery and potentiation effects within 2-min post-exercise with children. Greater potentiation is known to occur with submaximal contractions (Sale 2004) and in trained individuals (Sale 2002). Since the children in our study were trained athletes but may not have been able to fully activate (i.e. they performed submaximal contractions), there is reason to believe that the two factors contributed to the potentiation observed. It was also suggested that potentiation may be dependent on the duration of the exercise and velocity of contraction (Chaouachi et al. 2011). Chaouachi et al. (2011) suggested that faster contractions and shorter duration would elicit greater potentiation. In the present study, the decreased potentiation following the high repetition (endurance) sets and greater potentiation following the low repetition (strength) sets may have been attributed to increased metabolites with the prolonged duration of the high repetition sets.

In addition, fatigue is not only characterized by reductions in maximal force output or performance (Asmussen and Mazin 1978; Degens and Veerkamp 1994; Fitts and Metzger 1993), but has also been defined as an increase in the perceived effort needed to exert a desired force (Enoka and Stuart 1992). With respect to evaluating perceived effort, RPE scores indicated that children had a lower perceived effort than adult (Armatas et al. 2010). This finding was supported by the children's lower maximal HR following the exercise sets, and may also explain why they were less fatigable than adults. Lower RPE scores may be related to the inability to produce a maximal effort (Barkley and Roemmich 2011). Barkley and Roemmich (2011) also suggested that the lower rating in children may be a result of lack of experience, and not having a previous reference point to compare perceived exertion. Although there is some discrepancy in the literature as some authors argue about a child's ability to rate their exertion (Williams et al. 1994) while others, utilizing child friendly scales, have reported otherwise (Faigenbaum et al. 2004).

As there were no significant signs of peripheral or central activation fatigue with the children, the significant decrease in number of repetitions and post-exercise MVC torque might be explained by the significant increase in antagonist activity. It has been suggested that decreased torque may be a result of the lack of coordination between agonist and antagonist activation (Paraschos et al. 2007). As coordination is known to play a role in executing motor tasks and has been shown to be age dependent it is also quite possible that the increased antagonist activity observed in children contributed to the decreased torque output and number of repetitions (Paraschos et al. 2007). One possibility may be a result of unfamiliarity with performing the contraction (motor task). Paraschos et al. (2007) also suggested that the increased antagonist activity might be a result of the discomfort for children to perform maximal contractions (Paraschos et al. 2007). Other authors have not reported similar results (Bassa et al. 2005; O'Brien et al. 2009). Bassa et al. (2005) suggested that decreased torque in children is more likely due to a decreased efficiency of activating agonist muscles. Although the aforementioned studies did not attempt to induce fatigue, the increased antagonist activity in the present study might be a result of fatigue-induced impairments to motor control or coordination (Paraschos et al. 2007). Although high-level athletes have been reported to adjust motor coordination strategies to maintain task requirements with fatigue (Aune et al. 2008), it is possible that the background of the competitive athletes in the present study was not sufficient to overcome fatigue-related coordination difficulties due to the young age of the sample.

Children have been shown to recover more rapidly than adults using a variety of methods including cycle ergometers (Ratel et al. 2002), isokinetic (Zafeiridis et al. 2005), isometric (Armatas et al. 2010), and isotonic (Faigenbaum et al. 2008) contractions. In accordance with the literature, the children in the present study recovered more rapidly in all parameters (performance, neuromuscular, and cardiovascular) than adults following both exercise interventions.

Similar to the present findings, there is evidence of children recovering as quickly as 1-min post-exercise (Faigenbaum et al. 2008), whereas adults have reported fatigue or performance decrements for at least 3 min of recovery (Behm et al. 2002a). Children were able to produce more repetitions than the adult men following a 1-min recovery interval, regardless of intervention. Our results fall within the general guidelines which state that rest intervals for children can range from 1 to 3 min when resistance training (Faigenbaum et al. 2009).

With respect to HR recovery, children's HR returned to baseline values following the 1-min recovery intervals in both protocols, whereas the adults remained elevated. These findings are supported in the literature (Ratel et al. 2002; Zafeiridis et al. 2005). It has been suggested that a greater relative capillary density may be responsible for the faster recovery in children (Falk and Dotan 2006). Aside from aforementioned rationales for the decreased fatigue in children (fiber types, decreased muscle activation), other studies have also attributed a quicker recovery in children to lower reliance on glycolysis (Ratel et al. 2006), quicker phosphocreatine resynthesis (Taylor et al. 1997), faster acid base regulation (Boisseau and Delamarche 2000), and increased fatigue resistance due to a lower power output (Falk and Dotan 2006).

Conclusion

The prepubescent boys illustrated some fatigue-induced impairments as attributed by a decrease in the resistance exercise repetitions, decrease in post-test MVC's and greater antagonist activity. Despite the increase in fatigue, the boys were able to recover faster than adults and the impairments sustained by adults were more substantial and significant. Although the fatigue incurred by the children could not be explained by changes in peripheral nor central mechanisms, the increased antagonistic activity (hamstrings) suggested that the fatigue was more likely to be a result of muscle coordination difficulties (increased co-contractions). With respect to children and adults, potentiating effects, as well as the inability of the children to provide maximal efforts may have also contributed to the diminished fatigue measures. As a result of the findings, 1-min recovery intervals with resistance training programs for prepubescent children can be utilized for both low repetition and high repetition, strength and endurance exercises, respectively. Future studies should investigate the effectiveness of training programs tailored towards increasing strength and endurance in children while utilizing various rest intervals.

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