The electromyographic threshold in boys and men

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Abstract

Background: Children have been shown to have higher lactate- (La_{Th}) and ventilatory- thresholds (Ve_{Th}) than adults, which might be explained by lower levels of type-II motor-unit (MU) recruitment. However, the electromyographic threshold (EMG_{Th}), regarded as indicating the onset of accelerated type-II MU recruitment, has been investigated only in adults. **Purpose:** To compare the relative exercise intensity at which the EMG_{Th} occurs in boys vs. men. **Methods:** Participants were 21 men (23.4 ± 4.1 y) and 23 boys (11.1 ± 1.1 y), with similar habitual physical activity and peak oxygen consumption (VO_{2pk}) (49.7 ± 5.5 vs. 50.1 ± 7.4 ml·kg⁻¹·min⁻¹, respectively). Ramped cycle-ergometry was conducted to volitional exhaustion with surface EMG recorded from the right and left vastus lateralis muscles throughout the test (~10min). The composite right-left EMG root mean-square (EMG_{RMS}) was then calculated per pedal revolution. The EMG_{Th} was then determined as the exercise intensity at the point of least residual sum of squares for any two-regression-line division of the EMG_{RMS} plot. **Results:** EMG_{Th} was detected in 20/21 of the men (95.2%) and only in 18/23 of the boys (78.3%). The boys' EMG_{Th} was significantly higher than the men's (86.4 ± 9.6 vs. $79.7 \pm 10.0\%$ of peak power-output at exhaustion; $p < 0.05$). The pattern was similar when EMG_{Th} was expressed as percentage of VO_{2pk} . **Conclusions:** The boys' higher EMG_{Th} suggests delayed and hence lesser utilisation of type-II MU in progressive exercise, compared with men. The boys–men EMG_{Th} differences were of similar magnitude to those shown for La_{Th} and Ve_{Th} , further suggesting a common underlying factor.

Key words: Children, Exercise, Motor unit activation

Abbreviations

EMG – Electromyography

EMG_{Th} – ElectroMyoGraphic Threshold

HR – Heart Rate

La_{Th} – Lactate Threshold

MU / MUs – Motor Unit / Motor Units

MVC – Maximal Voluntary Contraction

OBLA – Onset of Blood Lactate Accumulation

PHV – Peak Height Velocity

Pmax – Maximal power attained at end of the EMG_{Th} test

PVO_{2pk} – Peak aerobic power (mechanical power output corresponding to VO_{2pk})

RER – Respiratory Exchange Ratio

RMS – Root Mean Square

SD – Standard Deviation

Ve_{Th} – Ventilatory / Gas-Exchange Threshold

VO₂ – Oxygen Consumption

VO_{2pk} – Peak oxygen consumption

Introduction

Children's response to exercise is physiologically and functionally different from adults'. For example, compared with adults, children demonstrate lower body-size-normalized maximal isometric strength (Falk et al. 2009) and short-term power (Beneke et al. 2007; Van Praagh and Dore 2002), higher ventilatory threshold (Ve_{Th}) (Klentreu et al. 2006) and lactate threshold (La_{Th}) (Simon et al. 1981; Tanaka and Shindo 1985). In terms of neuromuscular function, children have been shown to have lower motor-unit (MU) activation of the knee extensor muscles (Blimkie 1989; O'Brien et al. 2009, 2010), and a lower mean power frequency during sustained maximal voluntary contraction (MVC) (Halin et al. 2003). According to the size-principle (Henneman et al. 1965), the lower level of voluntary recruitment implies that children activate their higher threshold, fast-twitch, type-II MUs to a lesser extent than do adults. **The lesser activation of type-II MUs and greater reliance on slow-twitch, type-I MUs may, in turn,** explain many performance, metabolic, and neuro-motor differences between children and adults, beyond isometric muscle strength (Dotan et al. 2012). Direct supportive evidence for this **differential MU activation hypothesis** is lacking due to technical or ethical constraints associated with invasive techniques. **Hence,** new investigative approaches ought to be **explored in attempting** to further support or **refute** the hypothesis.

Currently, no technique is available for directly monitoring the proportion of active type-I vs. type-II MUs. Furthermore, invasive procedures that might be available for adults (*e.g.*, needle electrodes) are not ethically acceptable for children. A non-invasive technique that is widely accepted as being able to discern the onset of type-II MU activation, in adults, is the electromyographic threshold (EMG_{Th}) (Candotti et al. 2008; Edwards and Lippold 1956; Hug et al. 2006b; Hug et al. 2003; Lucia et al. 1999; Maestu et al. 2006; Moritani and deVries 1978;

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4 Moritani et al. 1993; Moritani et al. 1984; Nagata et al. 1981; Petrofsky 1979; Tikkanen et al.
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7 2012). The EMG_{Th} is defined as a non-linear increase, or upward inflection, in the EMG signal
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9 during progressive exercise of increasing intensity (Miyashita and Kanehisa 1980; Moritani and
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11 deVries 1978). The EMG_{Th} concept is supported by evidence of orderly depletion of glycogen
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13 first in type-I and II_A , followed by II_{AX} (II_{AB}), and finally II_X (II_B) muscle fibres at increasing
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15 workloads (Vollestad and Blom 1985), and by increasing muscle fibre conduction velocity at
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17 progressively higher power outputs, suggesting progressive recruitment of large, high-
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19 conduction-velocity MUs with increasing muscle force (Farina et al. 2004).
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24 In adults, the EMG_{Th} has been investigated in untrained as well as trained individuals,
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26 mostly in cycling and running, but also in upper-extremity exercise modes (Bearden and Moffatt
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28 2001; Candotti et al. 2008; Chwalbinska-Moneta et al. 1994; Chwalbinska-Moneta et al. 1998;
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30 Hug et al. 2004; Hug et al. 2006b; Hug et al. 2003; Lucia et al. 1999; Moritani et al. 1993;
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32 Nagata et al. 1981; Takaishi et al. 1992; Taylor and Bronks 1994; Tikkanen et al. 2012; Viitasalo
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34 et al. 1985), and in a wide range of muscles (Bearden and Moffatt 2001; Chwalbinska-Moneta et
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36 al. 1994; Chwalbinska-Moneta et al. 1998; Hug et al. 2006b; Hug et al. 2003; Lucia et al. 1999;
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38 Moritani et al. 1984; Nagata et al. 1981; Takaishi et al. 1992). Alongside the EMG_{Th} , a number
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40 of studies also determined the Ve_{Th} (Nagata et al. 1981; Tikkanen et al. 2012), the La_{Th} (Candotti
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42 et al. 2008; Chwalbinska-Moneta et al. 1998; Moritani et al. 1993; Moritani et al. 1984; Nagata
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44 et al. 1981), and the onset of blood lactate accumulation (OBLA) (Tikkanen et al. 2012). These
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46 thresholds highly correlated with the EMG_{Th} , although they did not necessarily coincide. This
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48 inter-threshold correlation could be expected as increased activation of the more glycolytic type-
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50 II MUs, presumed to occur at the EMG_{Th} , implies higher lactate production and accumulation,
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52 increased acidosis, and elevated ventilatory drive.
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The EMG_{Th} has not been studied in children. Thus, the purpose of this study was to compare the relative exercise intensity at which EMG_{Th} occurs in children vs. adults. Given the close relationships between EMG_{Th} and the La_{Th} and Ve_{Th} seen in adults, and the observed higher exercise intensity at which the latter thresholds occur in children, it was hypothesized that the EMG_{Th} would also occur at higher relative exercise intensities in children than in adults. Such findings would suggest a different muscle activation regimen, in which children recruit type-II MUs later and to a lesser extent than do adults.

Methods

Participants

All tests and procedures complied with the Helsinki declaration and were cleared by Brock University's Research Ethics Board. Twenty three boys, aged 8–13 y, and 21 men, aged 18–32 y, with similar weekly physical activity history and peak oxygen consumption (VO_{2pk}), volunteered for the study. A summary of participants' characteristics is provided in Table 1. Written informed consent was provided by all adult participants and by the boys' parents or guardians prior to enrolment in the study. All boys provided their informed assent to participate. Participants completed questionnaires regarding medical history, physical activity (Godin and Shephard 1985) and sport training history. All participants were physically active and all child participants were involved in some form of organized, competitive sports. Boys were significantly smaller than men but no differences were observed in body composition or maximal oxygen consumption. Sexual maturity in the boys, as determined by self-assessment of secondary sex characteristics [pubic hair (Tanner 1962)], ranged from stages 1 to 4, with eight boys at stage 1, eight at stage 2, five at stage 3, and one at stage 4. One participant's sexual

maturity value was excluded from analysis due to misreport concerns. Years to age of Peak Height Velocity (PHV) for the boys, as estimated using the Mirwald equation (Mirwald et al. 2002), averaged -2.30 ± 0.63 years ($n=18$; range: -0.88 to -3.59).

[Table 1]

Experimental Protocol

Participants made two laboratory visits. During the first visit, participants were informed of all tests and procedures to take place over both visits. Anthropometric variables such as height, body mass, and percent body fat (%Fat) were measured. Skinfold thickness was measured in triplicate using Harpenden calipers (British Indicators, Herts, England) and the median value at each site was used. Skinfold thickness (triceps and subscapula) was used to estimate percent body fat using age- and maturity-specific equations (Slaughter 1988). Pubertal stage and physical activity and training history were also determined. Participants were then familiarised with the crank-length-adjustable cycle-ergometer (Excalibur Sport, Lode, Groningen, The Netherlands). Seat and handlebar positioning were determined and recorded for re-use in the subsequent visit. Proper crank length was individually determined at 5-mm increments as a function of inseam length. Participants then proceeded to perform a submaximal and maximal progressive cycling test to determine aerobic capacity (see below).

The second visit was scheduled 3–7 days following the first visit and included a maximal progressive cycling test for the determination of the EMG_{Th} (see below).

Exercise Testing

Submaximal VO_2 and VO_{2pk} tests (Visit 1): Following a 5-minute warm-up period, participants commenced an incremental exercise protocol consisting of 3–5 submaximal stages to determine the VO_2 -vs.-power relationship. Stages were 3.5- and 4-min long for the boys and

the men, respectively. Boys started out at 40– 60W and progressed in 15– 20W increments at each subsequent stage. Men started at 80–100W with 30–40W increments. These submaximal stages were used to determine the steady-state VO_2 in several progressive power output levels.

Following the completion of the submaximal stages, participants recovered for 10–20-min. Participants then performed an incremental exercise protocol to volitional exhaustion for the determination of peak aerobic power ($\text{PVO}_{2\text{pk}}$; the power output, in Watts, corresponding to $\text{VO}_{2\text{pk}}$). Workload was increased every minute (10 and 20 $\text{W} \cdot \text{min}^{-1}$, for the boys and men, respectively) until volitional exhaustion. Pedalling rate was maintained at a minimum of 80 revolutions per minute (rpm).

Heart rate was determined using a heart rate monitor (Timex Personal Heart Rate Monitor, Timex Group Inc., Toronto, ON) throughout the test. Expired gas was collected and analyzed using the Moxus metabolic cart (AEI technologies, PA, USA), calibrated prior to each test. $\text{VO}_{2\text{pk}}$ was determined as the average of the highest VO_2 values attained over three consecutive 15-s periods.

EMG_{Th} test (Visit 2): Ryan & Gregor (Ryan and Gregor 1992) showed that the mono-articular muscles gluteus maximus, vastus lateralis (VL), vastus medialis, tibialis anterior, and soleus play a relatively invariant role as primary power producers in cycling. Hug *et al.* (Hug et al. 2006b) showed VL to be the most consistent of eight cycling-involved muscles in demonstrating the EMG_{Th}. We therefore chose VL as our tested muscle.

Following a 5-minute warm-up period, participants performed a ramped incremental cycling test to exhaustion. Starting power output was set at ~35– 40% of $\text{PVO}_{2\text{pk}}$ and, based on the previously-determined $\text{PVO}_{2\text{pk}}$, the ramp protocol was set so as to reach volitional exhaustion

after ~10 min of exercise. Thus, the mean starting power output for the boys was 51 ± 12 W and power output increased on average 1W every 6 s. The corresponding values for men were 103 ± 21 W and 1 W every 3 s. Surface EMG, using 10 mm², bipolar, Ag/Ag surface electrodes (Delsys 2.1, Delsys Inc., Boston, MA), was used to continuously monitor the VL EMG of each leg throughout the test. An area of each thigh at two-thirds on the line from the anterior spina iliaca superior to the superior border of the patella was shaved (if necessary), abraded with skin preparation gel (Nuprep, Weaver and Company, Aurora, CO), and cleaned with rubbing alcohol. Electrodes were placed parallel to the direction of muscle fibres on the medial aspect of the VL and affixed with proprietary double-sided tape. A reference electrode was placed over the spinous process of the seventh cervical vertebra. Participants were instructed and supervised to maintain a pedalling rate as close to 80 rpm as possible throughout the test and verbal encouragement was provided throughout the test and particularly as the participant approached exhaustion.

EMG Data Reduction

EMG signals were band-pass filtered (20– 450 Hz) using the Bagnoli-4 (Delsys Inc., Boston, MA) bioamplifier and sampled at a rate of 1000 Hz using a Computer-Based Oscillograph and Data Acquisition System (EMGworks Acquisition, Delsys Inc., Boston, MA).

EMG data were analyzed using a dedicated computer algorithm created in MATLAB (2013 version; MathWorks Inc., Natick, MA). For each pedal stroke, a succinct EMG burst was defined and recorded for each leg and the record was pruned at the beginning and end of each stroke to remove any partial or incomplete bursts, if any. The pruned waveform was then de-trended to offset any baseline deviation (*i.e.*, set baseline value to zero). The root mean square (RMS_{EMG}) was then calculated for each stroke throughout the entire EMG trace. The onset and offset of

each RMS_{EMG} burst were identified as the points where RMS_{EMG} rose or fell, respectively, above or below 10% of the mean RMS_{EMG} value of the entire test record. The mean RMS_{EMG} of each burst (*i.e.*, between the onset and offset) was then extracted for EMG_{Th} determination.

EMG_{Th} Determination

A composite plot, averaging the RMS_{EMG} bursts from both legs, was constructed for each participant. This plot consisted of RMS_{EMG} values (one for each pedal stroke) plotted against the test duration. To reduce the internal fluctuation, a trimmed moving average (30-point window in which the lowest 10 and highest 10 values were trimmed off and the mean of the median 10 points was calculated) was applied to the plot (Fig.1). In cases where a drop in the RMS_{EMG} at the end of the test was observed in conjunction with a sustained fall below 80 rpm in pedalling cadence, the plot was truncated at the point where cadence began to fall. The EMG_{Th} was then determined by a computer algorithm as the point of least residual sum of squares for any two linear regression-line divisions of the data, similar to the approach of Hug *et al.* (Hug *et al.* 2006a).

[Figure 1]

Since the algorithm would always determine a point of least residual sum of squares, even when no actual threshold exists, an additional criterion was used to qualify a threshold. Based on previous literature (Hug *et al.* 2006b), EMG_{Th} was expected to occur at relative power outputs higher than $\sim 80\% P_{\text{max}}$ in adults, and we hypothesise this to be even higher in children. Based on this assumption, a linear regression line was determined for the initial 70% of the test duration, corresponding to $\sim 80\%$ of P_{max} (since the EMG_{Th} test commenced at a power output equal to $\sim 35\text{--}40\%$ of $\text{PVO}_{2\text{pk}}$). That line was extrapolated to the entire test duration. A 3-standard-deviation (SD) confidence interval was applied above the trend line and extended to the end of

the trace (Fig.1). An EMG_{Th} was then confirmed only if the RMS_{EMG} plot rose and stayed above the confidence limit (*e.g.*, Fig.1), without descending back to within the confidence interval until the end of the test (*e.g.*, Fig.2). For those participants showing a threshold, the power output at the EMG_{Th} time point was determined. This power output was expressed as a percentage of the peak power output reached during the EMG_{Th} test ($\%P_{max}$) and as a percentage of VO_{2pk} ($\%VO_{2pk}$), based on the data obtained from the first session's VO_2 testing.

[Figure 2]

Statistical Analysis

All statistical analysis was performed using SPSS v.20 (SPSS Inc., Chicago, IL). The data for all groups are presented as means $\pm$ 1 SD. All data were normally distributed. Group differences in physical characteristics and $\%P_{max}$ and $\%VO_{2pk}$ at EMG_{Th} were assessed using a two-tailed, homoscedastic Student's t-test. Additionally, group differences between 'Responders' and 'Non-Responders' (see Results section) were examined using a two-tailed Student's t-test. Despite the small sample size, assumptions for normal distribution and homogeneity of variance were met. Pearson's Correlations were computed for the boys, men, and the combined groups, between the EMG_{Th} (both as $\%VO_{2pk}$ and $\%P_{max}$) and $VO_{2pk} \cdot kgBW^{-1}$, $PVO_{2pk} \cdot kgBW^{-1}$, $P_{max} \cdot kgBW^{-1}$, leisure time physical activity, and training hours per week, respectively. The acceptable level of significance for all tests was set at $p < 0.05$.

Results

Physical activity scores and training histories were similar in the two groups (Table 1). Importantly, peak heart rate was, on average, 4 bpm higher in the boys whose VO_{2pk} was also

marginally higher. While none of these differences reached statistical significance they do strongly suggest that the boys had attained a comparable level of exertion to that of the men.

An EMG_{Th} was identified in 20 out of the 21 men (95.2%) and in 18 of 23 boys (78.3%) ($\chi^2_{(1, n=44)}=2.69, p=0.10$). In the participants for whom a threshold was identified, group differences showed 6.6% higher (later) $EMG_{Th} \%P_{max}$ in the boys compared with the men ($t_{(36)}=-2.08, p=0.045$) ($86.4\pm9.6\%$ vs. $79.7\pm10.0\%$, respectively; Fig.3). There was also a trend for a higher $EMG_{Th} \%VO_{2pk}$ in the boys vs. men ($t_{(35)}=-1.62, p=0.12$) (101.2 ± 11.4 vs. $94.8\pm12.2\%$, respectively; Fig.3) (only 17 boys included. VO_2 data could not be obtained for one boy).

[Figure 3]

Correlational analyses revealed that for all participants, $EMG_{Th} (\%VO_{2pk})$ was not correlated with body-mass-normalized VO_{2pk} ($VO_{2pk}\cdot kg^{-1}$) ($r=-0.18, p>0.05$). However, when examined separately for each group, a significant negative correlation was observed in the boys ($r=-0.51, p=0.015$), but not in the men ($r=0.18, p>0.05$). Also, $EMG_{Th} (\%VO_{2pk})$ similarly correlated with the power output at $VO_{2pk}\cdot kg^{-1}$ ($PVO_{2pk}\cdot kg^{-1}$) in the boys ($r=-0.52, p=0.03$) (Fig.4), but not in the men. No significant correlations were found between $EMG_{Th} \%P_{max}$ or $EMG_{Th} \%VO_{2pk}$ and training history, or leisure time physical activity.

[Figure 4]

For further analysis, the boys who demonstrated EMG_{Th} ('Responders', $n=18$) were compared to those who did not ('Non-responders', $n=5$) (Table 2). The 'Responders' had significantly longer mean test duration than the 'Non-responders' ($p=0.016$) as well as

significantly greater Pmax/PVO₂pk ratio (p=0.027). There were no statistically significant differences in any other variables.

In the men's group, only one participant did not show an EMG_{Th}. He had exceptionally-high VO₂pk·kg⁻¹ and PVO₂pk·kg⁻¹ values that were ~2.5 SDs above the group's mean.

[Table 2]

Discussion

The main findings of this study are that **a**) EMG_{Th} was identified in only 78.3% (18/23) of the boys, while the corresponding value in the men was 95.2% (20/21); and **b**) Among those in whom EMG_{Th} was detected, the boys' EMG_{Th} occurred at significantly higher relative workloads compared with the men. As the EMG_{Th} is widely believed to reflect the onset of accelerated increase in higher-threshold, type-II MU recruitment during progressive exercise (Edwards and Lippold 1956; Hug et al. 2006b; Hug et al. 2003; Lucia et al. 1999; Maestu et al. 2006; Moritani and deVries 1978; Moritani et al. 1993; Moritani et al. 1984; Nagata et al. 1981; Petrofsky 1979; Tikkanen et al. 2012), these findings suggest that boys activate their type-II MUs later and for a shorter duration than do men.

The results for our men's group are in close agreement with previous findings (Hug et al. 2006b; Lucia et al. 1999; Takaishi et al. 1992). However, to our knowledge, this is the first study to investigate the EMG_{Th} in children. Compared with the men, our boys' higher relative EMG_{Th} is in line with our hypothesis, based on known boys–men differences in La_{Th} and Ve_{Th}. Our observed differences of 6.6 %P_{max} and 6.4 %VO₂pk are similar to previously reported boys–men %VO₂pk differences in Ve_{Th} [7.2%, (Klentreu et al. 2006); 8.9%, (Anderson and Mahon 2007)] and La_{Th} [9.1%, (Anderson and Mahon 2007)] during cycling exercise.

A question arising from our findings is why EMG_{Th} could not be detected in the five ‘Non-responder’ boys? At exhaustion, the force applied by the participating muscles is considerably lower than MVC for the given pedalling cadence (Greig et al. 1985; Sargeant et al. 1981). In view of the fact that 50% of ‘Responders’ EMG_{Th} occurred very close to exhaustion (>92% P_{max}), it is conceivable that the five ‘Non-Responders’ terminated their tests before attaining the force level at which EMG_{Th} would have taken place. That is, had they been able to continue exercising longer, their EMG_{Th} would have occurred at their observed power at exhaustion or above it. This suggestion is supported by our finding that, in the ‘Responders’, body-mass-normalized peak aerobic power (PVO_{2pk}/kg) negatively correlated with EMG_{Th} %VO_{2pk} ($r=-0.52$, $p=0.03$; Fig.4). That is, in boys with lower maximal power output, EMG_{Th} was attained closer to maximal aerobic power, compared with more powerful boys. This, in turn, suggests that ‘Non-responders’ may not have been able to produce the power and thus the contractile force required to manifest the EMG_{Th}. Further support for the suggestion is provided by Vollestad & Blom (Vollestad and Blom 1985; Vollestad et al. 1984) who found that activation of type II_{AX} (II_{AB}) and II_X (II_B) MUs in adult men, during progressive cycling, took place only at 91% VO_{2pk} and beyond. As shown by Greig *et al.* (Greig et al. 1985), this power output level would require only ~50% of the maximal pedal force at that cadence.

Accepting the notion that EMG_{Th} could indeed occur at or above the peak force level attained in progressive exercise to exhaustion, means that EMG_{Th} would only be detected in those individuals able to exceed the critical force by the end of the progressive exercise test. It is conceivable then that ‘Non-Responders’ ended their tests prior to attaining the sufficiently high power output necessary to attain that critical force and elicit EMG_{Th}. Men attain higher relative force and power outputs due to their higher anaerobic capacity compared with the boys (Beneke

et al. 2007; Van Praagh and Dore 2002). Thus, most men produce the muscle force necessary for EMG_{Th} manifestation. For this reason, there was little or no correlation between EMG_{Th} and VO₂pk or PVO₂pk in the men, unlike in the boys. Support for this notion comes from the fact that compared with ‘Non-Responders’, ‘Responders’ had significantly longer test durations and higher Pmax/PVO₂pk ratio (Table 2). That is, ‘Responders’ were able to employ more anaerobic power after reaching their respective PVO₂pk and thus extend their test durations. Presumably, this was facilitated by the ‘Responders’ greater relative capacity to recruit type-II MUs.

The boys–men difference of 6.6% in EMG_{Th} %Pmax (boys=86.4%, men=79.4%; p=0.045) is likely an underestimate of group difference as it reflects only the ‘Responders’. Assigning just 100% as the EMG_{Th} %Pmax values for the six ‘Non-Responders’ (5 boys, 1 man), the overall boys–men EMG_{Th} difference increased by 30% to 8.6% (boys=89.3, men=80.7%; p<0.01). Accepting the possibility that EMG_{Th} could occur at >100% Pmax intensity, the true boys–men difference could well be even larger.

To illuminate possible underlying distinguishing factors, the ‘Responder’ and ‘Non-responder’ boys were compared (Table 2). On average, ‘Responders’ lasted 18% longer in their respective EMG_{Th} tests than did ‘Non-responders’. Accordingly, their final power output (Pmax) was 15.5% higher, although this difference did not reach statistical significance. Since initial loading and the ramping protocol of the EMG_{Th} test were based on peak aerobic power (PVO₂pk), >95% of participants attained a Pmax that was greater than PVO₂pk. However, while the ‘Responders’ Pmax was 17% higher, ‘Non-responders’ Pmax was only 5% higher than PVO₂pk (p<0.03). Again, this suggests that ‘Non-responders’ were less capable of recruiting the higher-threshold type-II MUs and generating the extra anaerobic power necessary to exceed PVO₂pk. The ‘Non-responders’ tended to be younger, lighter, and shorter; have lower lean body

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4 mass, be less physically active, and somatically less mature (longer time before PHV). Although
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6 none of these differences was statistically significant, the general picture is one of lower maturity
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8 level, which may be regarded as consistent with them possessing higher or no detectable EMG_{Th}.
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12 The only man in whom EMG_{Th} could not be detected, had the highest VO_{2pk} (63.6 ml·kg⁻¹·min⁻¹) and PVO_{2pk} (5.14 W·kg⁻¹), both of which were ~2.5 SD above the mean for the group.
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15 Since in comparable studies (*e.g.*, (Hug et al. 2006a, b; Hug et al. 2003) the EMG_{Th} was detected
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17 in 100% of participants, we suggest that the absence of EMG_{Th} in this individual was not due to
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19 error and that his high aerobic capacity could have been due to particularly high type-I muscle-
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21 fibre composition. Thus, like the boy ‘Non-Responders’, he too might not have been able to
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23 sufficiently engage type-II MUs by the time he reached exhaustion.
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30 Given the previously demonstrated relationships between EMG_{Th} and both La_{Th} and Ve_{Th} in
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32 men (Candotti et al. 2008; Chwalbinska-Moneta et al. 1998; Moritani et al. 1993; Moritani et al.
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34 1984; Nagata et al. 1981; Tikkanen et al. 2012), similar relationships presumably exist in boys,
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36 as well. In both men and boys, however, there is a persistent difference between exercise
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38 intensity at La_{Th} or Ve_{Th} *vs.* that of EMG_{Th}. For example, in men, La_{Th} and Ve_{Th} have been
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40 typically found between ~50–60 %VO_{2pk} (Anderson and Mahon 2007; Klentrou et al. 2006;
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42 Simon et al. 1986), while EMG_{Th} has been identified at ~90 %VO_{2pk} (Lucia et al. 1999;
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44 Takaishi et al. 1992) and at 94.8 %VO_{2pk} in the present study. The corresponding values for
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46 boys are ~60–70 %VO_{2pk} for La_{Th} & Ve_{Th} (Anderson and Mahon 2007; Klentrou et al. 2006)
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48 and 101.2 %VO_{2pk} for EMG_{Th} (in the present study). While boys’ values are generally ~10%
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50 higher than the men’s, the differences between the EMG_{Th} and the La_{Th} or Ve_{Th} thresholds are
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52 rather similar: ~45% in both groups. A notable exception to this pattern is Candotti *et al.*’s
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54 finding of nearly identical EMG_{Th} and La_{Th} values in adult recreational cyclists (Candotti et al.
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2008). A partial explanation for this discrepancy is the La_{Th} protocol used by Candotti *et al.* (continuous, 3-min stages), which overestimates La_{Th} due to the delay in the lactate response to the fast changing workloads. Furthermore, the testing protocol was exhaustion-limited at $\sim 200W$, likely due to lactate accumulation and well before VO_{2pk} or PVO_{2pk} could be reached. Thus, the mean reported EMG_{Th} (134W) occurred at no more than $\sim 67\%$ of the end-of-protocol power and in reality likely constituted VO_{2pk} percentage considerably lower than that. Since Hug *et al.* detected two rather than a single EMG_{Th} in professional cyclists (at 52 and 86% VO_{2pk}) (Hug *et al.* 2003), it is conceivable that the EMG_{Th} reported by Candotti *et al.* (Candotti *et al.* 2008) is the first (lower) rather than the second of the two thresholds.

The typical magnitude of the $EMG_{Th} - La_{Th}$ difference appears to suggest that the EMG_{Th} phenomenon is independent of the factors governing La_{Th} and Ve_{Th} , but the apparent consistency of this difference in men and boys seems to suggest otherwise. Several factors should be considered in explaining the apparent $EMG_{Th} - La_{Th}/Ve_{Th}$ discrepancy: **a.** While La_{Th} and Ve_{Th} are systemic, whole-body phenomena, the EMG_{Th} is confined to a single-muscle. **b.** The metabolic acidosis and increased lactate production that underlie both La_{Th} and Ve_{Th} , take place as a function of increasing exercise intensity in the active MUs and could occur regardless of whether or not higher-threshold MUs are involved. EMG_{Th} , on the other hand, is presumably dependent on type-II MU involvement and could thus occur considerably after La_{Th} or Ve_{Th} have already taken place. **c.** Based on evidence such as Vollestad & Blom's glycogen depletion findings (Vollestad and Blom 1985), La_{Th} and Ve_{Th} could be related to increased type-II_A MU recruitment, which occurs at low or moderate intensities. The EMG_{Th} , on the other hand, might be associated with recruitment of the fast-twitch MU types II_{AX} (II_{AB}) and II_X (II_B), which typically occurs in the later part of exhaustive exercise.

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4 It may be of interest to draw an analogy between children and elite adult endurance athletes.
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6 Compared with untrained men, boys are characterized by markedly higher thresholds of all 3
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8 types (La_{Th} , Ve_{Th} , EMG_{Th}). The same has been shown to be true for endurance athletes, in whom
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10 the higher thresholds are attained by extensive training at moderate intensities that, according to
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12 the size principle (Henneman et al. 1965) and glycogen depletion data (Vollestad and Blom
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14 1985; Vollestad et al. 1984), predominantly recruit type-I and possibly the lower portion of the
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16 type-II_A MU pool. Also, such athletes often possess higher type-I MU composition to begin with
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18 (Costill et al. 1976). Consequently, adult endurance athletes utilize type-I MUs to a greater
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20 extent than do non-athletes. The present data indicate that children (boys) are characterized by
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22 lower utilization of type-II MUs and thus, greater reliance on type-I MUs utilization as is the
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24 case in endurance athletes. The difference is that in children this is not due to training or talent,
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26 but rather to what we suggest is their lower utilization of type-II MUs.
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33 **Conclusions**

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35 Our findings suggest that the fundamental nature of MU recruitment in progressive exercise
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37 [Henneman's size principle; (Henneman et al. 1965)] is qualitatively similar in boys and men.
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39 There is, however, a significant quantitative difference in that the boys' EMG_{Th} occurred at
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41 higher exercise intensities compared with the men's. This age-related difference suggests later
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43 recruitment of higher threshold MUs in boys and is in line with previous findings of higher
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45 relative La_{Th} and Ve_{Th} in boys compared with men. These findings support the child-adult
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47 differential MU-activation hypothesis. We suggest that this support is particularly insightful
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49 since the EMG_{Th} is currently the best non-invasive 'window' into the type of differential MU
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51 activation at the core of the hypothesis.
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Competing Interests

The authors have no competing interests to declare.

Figure Legends

Figure 1. A representative RMS_{EMG} trace of an adult man participant. Note the clear rise of the trace above the $+3\text{SD}$ confidence interval.

Figure 2. A representative RMS_{EMG} trace of a boy participant. No EMG_{Th} is identifiable in this trace.

Figure 3. Group differences in relative exercise intensity at the EMG_{Th} between boys and men in whom EMG_{Th} was identified ('Responders'). Values are $\text{Mean} \pm 1\text{SD}$.

* = boys significantly higher than men, $p < 0.05$.

Figure 4. Correlation between peak aerobic power ($\text{PVO}_{2\text{pk}}$) and EMG_{Th} as $\% \text{VO}_{2\text{pk}}$ for the boys who showed EMG_{Th} ($n=17$; VO_2 data unavailable for one boy).

Tables

Table 1. Participants' physical characteristics and training histories. Values are Means $\pm$ 1SD.

	Men	Boys
n	21	23
Age (y)	23.4 $\pm$ 4.1	11.1 $\pm$ 1.1*
Mass (kg)	75.4 $\pm$ 10.4	37.1 $\pm$ 7.5*
Height (cm)	181.5 $\pm$ 6.3	145.7 $\pm$ 8.6*
%Fat	14.0 $\pm$ 3.6	14.2 $\pm$ 3.2
Activity Score	79.1 $\pm$ 50.9	81.6 $\pm$ 25.3
Sport training (hours $\cdot$ week ⁻¹)	5.6 $\pm$ 4.8	5.4 $\pm$ 2.6
VO ₂ pk (ml $\cdot$ kg $\cdot$ min ⁻¹)	49.7 $\pm$ 5.5	50.1 $\pm$ 7.4
RER at VO ₂ pk	1.15 $\pm$ 0.06	1.05 $\pm$ 0.08*#
HR at VO ₂ pk (bpm)	194 $\pm$ 7	198 $\pm$ 11

* – Significant difference between groups, $p < 0.05$

– n=22 (VO₂ data unavailable for one boy)

Table 2. Comparison between EMG_{Th} ‘Responders’ and ‘Non-Responders’ among the boys.
Values are Means $\pm$ 1SD.

	‘Responders’	‘Non-Responders’
n	18	5
Age, years	11.1 $\pm$ 1.2	11.1 $\pm$ 0.8
Years to age of PHV	2.26 $\pm$ 0.68	2.52 $\pm$ 0.32
Body mass, kg	38.0 $\pm$ 7.9	34.0 $\pm$ 5.0
Height, cm	146.8 $\pm$ 9.0	141.7 $\pm$ 6.4
Lean Body Mass, kg	32.4 $\pm$ 6.2	29.2 $\pm$ 3.8
Activity score	83.5 $\pm$ 27.3	74.9 $\pm$ 16.9
VO ₂ pk, ml·kg ⁻¹ ·min ⁻¹	50.5 $\pm$ 7.8	48.9 $\pm$ 6.1
EMG _{Th} test duration, s	598 $\pm$ 65	507 $\pm$ 67 *
Pmax/kg, W·kg ⁻¹	4.02 $\pm$ 0.65	3.88 $\pm$ 0.43
Pmax/PVO ₂ pk ratio	1.17 $\pm$ 0.09	1.05 $\pm$ 0.09 *

* = Significant difference between groups; $p < 0.05$

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