Pre-exhaustion Exercise Differentially Influences Neuromuscular Fatigue Based on Habitual Physical Activity History

Kenneth G. Harlan,[1,2] Roberto B. Merucci,[1,2] Jalen J. Weaver,[1,2] Thomas C. Windle,[1,2] and Moh H. Malek[1,2]

[1]*Department of Health Care Sciences, Physical Therapy Program, College of Pharmacy and Health Sciences, Wayne State University, Detroit, Michigan; and* [2]*Department of Health Care Sciences, Integrative Physiology of Exercise Laboratory, College of Pharmacy and Health Sciences, Wayne State University, Detroit, Michigan*

Abstract

Harlan, KG, Merucci, RB, Weaver, JJ, Windle, TC, and Malek, MH. Pre-exhaustion exercise differentially influences neuromuscular fatigue based on habitual physical activity history. *J Strength Cond Res* XX(X): 000–000, 2018—Although there is anecdotal evidence of a potential physiological benefit of pre-exhaustion exercise to enhance muscular recruitment, few studies have systematically examined the effect on neuromuscular activity. Moreover, a subject's habitual physical activity history may, in part, contribute to the muscle's response on a subsequent workbout after a single pre-exhaustion workbout. To date, no studies have examined the effect of pre-exhaustion exercise on the electromyographic fatigue threshold (EMG_{FT}). The purpose of this study, therefore, is to determine whether pre-exhaustion exercise influences the EMG_{FT}. Specifically, we were interested in determining whether or not there is a dichotomous response to pre-exhaustion exercise based on the individual's habitual physical activity history. Thus, we hypothesized that healthy active subjects would have reduced EMG_{FT} values, whereas elite runners would have increased EMG_{FT} values as a result of the pre-exhaustion exercise. Eight healthy college-aged men (mean ± *SEM*, age = 24.5 ± 0.3 years; body mass = 83.1 ± 3.0 kg; and height = 1.80 ± 0.02 m) and 9 elite runners (mean ± *SEM*, age = 23.4 ± 0.7 years; body mass = 70.3 ± 2.7 kg; and height = 1.79 ± 0.03 m) participated in current study. Each subject visited the laboratory on 2 occasions separated by 7 days and performed the single-leg knee-extensor ergometry test. For one of the visits, the subjects performed the Thorstensson test (50 continuous, concentric knee extensions) before the single-leg knee-extensor ergometry. The EMG_{FT} was measured on both visits for all subjects. For healthy subjects, we found that the EMG_{FT} was significantly reduced after performing the 50 isokinetic knee extensions (control: 27 ± 6 W vs. Thorstensson: 21 ± 6.0 W; $p = 0.001$), whereas for elite runners, there was no significant mean differences between the 2 visits (control: 38 ± 3 W vs. Thorstensson: 39 ± 2 W; $p = 0.813$). These results suggest that 50 repetition of isokinetic muscle action, as a method of pre-existing the quadriceps femoris muscles, may be influenced by the subject's habitual exercise history.

Key Words EMG fatigue threshold, activation, motor unit

Introduction

Priming exercise typically involves the subject performing an exercise workload followed by a specific rest period and then again performing the same exercise workload. For aerobic workloads, studies tend to suggest that priming exercises in the low or moderate intensity (40–60% of maximal oxygen uptake) domain are less effective than workloads in the high exercise intensity (70–80% of maximal oxygen uptake) domain (19). Similarly, for resistance training, the term "pre-exhaustion" is used to indicate the potential priming of the muscle (1,11). The unique feature, however, of pre-exhaustion exercise is that a single-joint exercise for the muscle of interest is used first and then followed by the multijoint exercise for that same muscle (1,11). For both aerobic and resistance training paradigms, the objective of priming (or pre-exhaustion) is to improve the muscles' responsiveness to the subsequent workbout. Although there is anecdotal evidence of a potential physiological benefit of pre-exhaustion to enhance muscular recruitment, few studies have systematically examined the effect on neuromuscular activity.

A noninvasive method of determining neuromuscular activity is the use of surface electromyography (EMG). Surface EMG is used to determine the activation of a muscle or group of muscles under various exercise paradigms

Address correspondence to Dr. Moh H. Malek, en7488@wayne.edu.

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ranging from mild to high intensity (4,10,13). One domain of the EMG signal, often studied, is the amplitude that indicates muscle recruitment, firing rating, or a combination of both (2,23). The EMG amplitude is a robust marker of neuromuscular activity and has been shown to have high intersession reliability (36). Moreover, studies have used the EMG amplitude to determine knee extension strength in various populations ranging from elite athletes (18) to clinical patients (27). Another utility of surface EMG is to determine training-induced neuromuscular changes after an extensive rehabilitation program (34).

Studies using the EMG signal to determine potential changes in the muscle activation using the pre-exhaustion paradigm have primarily focused on muscles of the upper body and exercises associated with resistance training (6,33,37). Moreover, the measurement of the EMG signal is at a single time point, which is then normalized to the subject's maximal voluntary contraction for comparisons across different conditions. Although this approach may be optimal for measuring muscle recruitment during strength-type exercises, it may not translate to incremental aerobic-type exercises where the exercise intensity increases periodically throughout the workbout.

One mathematical model that uses the EMG amplitude is the single-visit EMG fatigue threshold (EMG_{FT}). In this paradigm, subjects perform aerobic exercise in which there is an increment in the intensity of the workload from mild to maximal over a 12- to 15-minute period (12). At each stage of the protocol, the EMG amplitude is recorded from the muscle of interest (12). Thereafter, linear regression is used to identify the highest power output with a nonsignificant slope and the lowest power output with a significant slope, which are then averaged (12). Briscoe et al. (7) and Galen and Malek (13) validated the EMG_{FT}, whereas Mahmutović et al. (22) reported high intersession reliability. Therefore, the EMG_{FT} may provide a unique advantageous of determining potential changes in neuromuscular fatigue from an external perturbation.

To date, no studies have examined the effect of pre-exhaustion exercise on the EMG_{FT}. The purpose of this study, therefore, is to determine whether pre-exhaustion exercise influences the EMG_{FT}. Specifically, we were interested in determining whether or not there is a dichotomous response to pre-exhaustion exercise based on the individual's habitual physical activity history. Thus, we hypothesized that healthy active subjects would have reduced EMG_{FT} values relative to the elite runners as a result of the pre-exhaustion exercise.

Methods

Experimental Approach to the Problem

Each subject visited the laboratory on 2 occasions separated by 7 days and performed the single-leg knee-extensor ergometry test. For one of the visits, the subjects performed the Thorstensson test (50 continuous, concentric knee extensions) before the single-leg knee-extensor ergometry. Moreover, EMG electrodes were placed over the rectus femoris muscle of each subject for the 2 visits. Previous studies (22) have shown no significant mean differences in the EMG_{FT} values for incremental single-leg knee-extensor ergometry. Moreover, it has been shown that the rectus femoris muscle is more active than the other 2 superficial quadriceps femoris muscles (32).

Subjects

Eight healthy college-aged men (mean ± *SEM*, age = 24.5 ± 0.3 years; body mass = 83.1 ± 3.0 kg; and height = 1.80 ± 0.02 m) and 9 elite runners (mean ± *SEM*, age = 23.4 ± 0.7 (21 to 27 years old); body mass = 70.3 ± 2.7 kg; and height = 1.79 ± 0.03 m) participated in current study. We operationally defined elite runners as individuals who, in the past 12 months, have completed the 5-km run in 17 minutes and 30 seconds based on the criteria provided by the World Masters Athletics (http://www.howardgrubb.co.uk/athletics/wmalookup15.html). In our sample of 9 elite runners, the average 5-km time was ~16 minutes (963 ± 14 seconds). The healthy college-aged men were individuals who were physically active, but did not participate in any organized or club athletic competitions. All subjects were asked to refrain from exercise 24 hours before their testing days. Subjects were also told not to consume any caffeine 24 hours before the testing sessions, but no other dietary restrictions were used. In addition, the 2 visits were performed at relatively the same time (±1 hour) for each visit. All procedures were approved by the Wayne State University Institutional Review Board for Human Subjects, and each participant signed an informed consent form before testing.

Procedures

Pre-exhaustion Workbout. For one of the visits, the subject was asked to perform the pre-exhaustion task (i.e., experimental visit), whereas the other visit (i.e., control visit) the pre-exhaustion task was absent. We used the Thorstensson test as the pre-exhaustion task because the muscle action mimics, in part, the single-leg knee-extensor ergometry. Briefly, this test consists of performing 50 continuous, concentric knee extensions at $180°\cdot s^{-1}$ on a dynamometer device (HUMAC NORM; CSMi, Inc., Stoughton, MA, USA) on the nondominant leg based on kicking preference. Immediately after the test (<2 minutes), the subject was moved to the single-leg knee-extensor ergometry device to perform the incremental test.

Incremental Single-Leg Knee-Extensor. The single-leg knee-extensor ergometry has been used previously in our laboratory (9,13,24,25,32) and exclusively focuses the exercise demand on the quadriceps femoris muscles (32). Briefly, each participant was semirecumbent in an adjustable chair with a special ankle boot placed on the nondominant leg and connected by a bar to the ergometer. The dominant leg was on a platform attached to the knee-extensor device (13,24,25,32). Contractions of the quadriceps muscles caused the lower part of the leg to extend through an angle of ~90° to ~10°. Therefore, the lower leg traveled with an arc-shaped trajectory of approximately 80° in an alternating manner (13,24,25,32). The momentum of the ergometer returned the relaxed leg passively to the start position, and, as a result, the quadriceps muscle was functionally isolated (13,24,25,32). After a period of stabilization at rest, participants began kicking at 4 W for 2 minutes. The power output was then increased by 4 W every minute throughout the test, until participants reached volitional fatigue. The cadence during the exercise workbout was maintained at 70 revolutions per minute (13,24,25). Termination of the exercise test was determined if the participant was unable to maintain the targeted kicking cadence, despite strong verbal encouragement (7). Subjects also wore a Polar Heart Watch system (Polar Electro, Inc., Lake Success, NY, USA) during the incremental test. Therefore, heart rate at the end of exercise was recorded. The relative heart rate at the end of exercise was determined using the equation 220 − age and converting to a percent value. Rating of perceived exertion for the exercised leg was taken using the Borg Modified Scale (0–10).

Determination of EMG_{FT}. For both visits, the EMG amplitude (microvolts root mean square, μVrms) was calculated from 6 data points for each 1-minute stage and then plotted vs. time (20). Thereafter, linear regression was performed to determine whether or not there was a significant increase in EMG amplitude across time for each power output. The EMG_{FT} was operationally defined as the average of the highest power output that resulted in a nonsignificant slope coefficient ($p > 0.05$) and the lowest power output that resulted in a significant ($p < 0.05$) positive slope coefficient (7,12,13,20).

Electromyography Electrode Placement. A single bipolar (20-mm, center-to-center) surface electrode (EL500-6; BIOPAC Systems, Inc., Santa Barbara, CA, USA) arrangement was positioned over the longitudinal axes of the rectus femoris muscle (13,24,25,32). This site was traced with a permanent marker for the subsequent visit to maintain the consistency of the electrode placement. The electrodes were placed at 50% the distance between the anterior superior iliac spine and the superior border of the patella (17). The reference electrode was placed over the iliac crest. The shaved skin at each electrode site was carefully abraded and cleaned with alcohol, and interelectrode impedance was kept below 2,000 ohms. The EMG signal from each electrode placement site was amplified (gain: ×1,000) using differential amplifiers (EMG 100B; BIOPAC Systems, Inc.) (13,24,25,32).

Electromyographic Signal Acquisition and Processing. The raw EMG signals were digitized at 1,000 Hz and stored in a personal computer (Dell Inspiron E1705; Dell, Inc., Round Rock, TX, USA) for subsequent analysis. All signal processing was performed using custom programs written with LabVIEW programming software (version 2014; National Instruments, Austin, TX, USA). The epochs for the 1-minute incremental protocol was 5 seconds, thus allowing for a total of 6 data points per power output as suggested by Khan et al. (20). The EMG signals were bandpass filtered (fourth-order Butterworth) at 10–500 Hz. The amplitude (microvolts root mean square, μVrms) value for each stage was calculated for each participant based on the average of all the completed bursts for each sampling window. The EMG mean power frequency domain was not analyzed because the studies have shown low reliability in this measure during incremental exercise (7).

Statistical Analyses

All data presented in the current investigation are mean ± *SEM*. As described in detail above, linear regression was used to determine the EMG_{FT}. Separate 1- and 2-way analyses of variance (ANOVAs) were performed for the different outcome variables. For each group, we analyzed the slope coefficients for the normalized (%max of the control) vs. exercise intensity relationships for the control and Thorstensson test visits as recommended by Pedhazur (31). All statistical significance was set at $p \leq 0.05$.

Table 1. Comparison of exercise indices for each group during the 2 visits (mean ± *SEM*).*†

	Healthy subjects		Elite runners	
Outcome variables	Control	Thorstensson	Control	Thorstensson
Maximal power output (W)	48 ± 3	48 ± 3	57 ± 3	59 ± 3
Heart rate at end of exercise ($b \cdot min^{-1}$)	148 ± 6	151 ± 4	131 ± 6	137 ± 4
Heart rate at end of exercise (% of predicted)	76 ± 3	77 ± 2	67 ± 3	70 ± 2
Maximal leg RPE (0–10)	10 ± 0	10 ± 0	9 ± 0	10 ± 0

*RPE = rating of perceived exertion.
†Heart rate % of predicted: 220 − age. No significant group × visit interaction. Refer to results section for significant main effect findings.

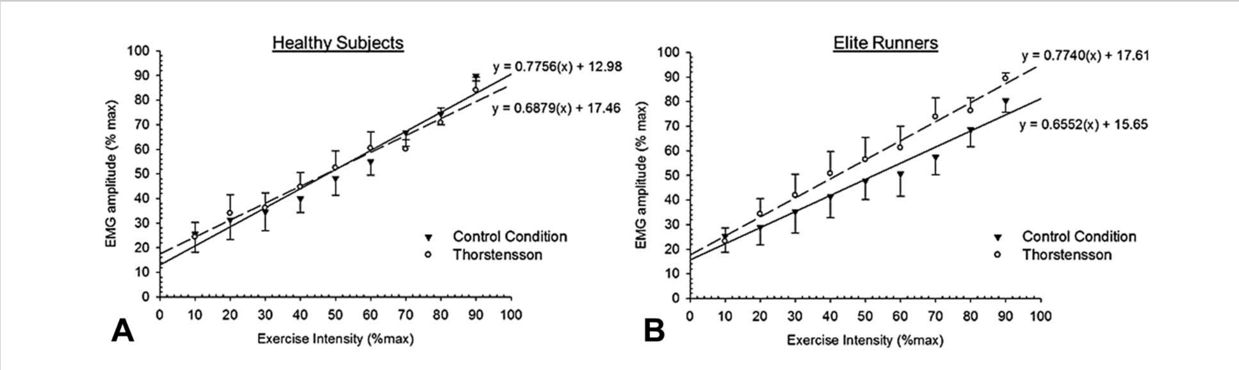

Figure 1. Depiction of the control group (panel A) and elite runners (panel B) normalized EMG amplitude vs. exercise intensity graph for each testing condition. For the healthy subjects (panel A), there was no significant difference between the slopes of the regression line for the 2 testing conditions. For the elite runners (panel B), there was a significant ($p = 0.041$) difference between the slopes of the regression line for the 2 testing conditions. EMG = electromyography.

Results

Incremental Exercise

As shown in Table 1, there were no significant (p values $\geq$ 0.35) group × visit interactions for the incremental exercise indices such as maximal power output, absolute and relative heart rate at end of exercise, and maximal leg rating of perceived exertion. For maximal power output, however, there was a significant main effect for group (healthy subjects: 48 ± 3 W vs. elite runners: 58 ± 3 W; $p = 0.036$). For the absolute heart rate at end of exercise, there was a significant main effect for group (healthy subjects: 149 ± 5 $b \cdot min^{-1}$ vs. elite runners: 134 ± 4 $b \cdot min^{-1}$; $p = 0.026$), whereas for the relative (% predicted max) heart rate at end of exercise, there was a significant main effect for group (healthy subjects: 76 ± 2% vs. elite runners: 68 ± 2%; $p = 0.021$).

Estimated EMG_{FT}

To analyze mean differences in the EMG_{FT} between the 2 groups, we first wanted to determine whether there were any pre-existing differences in the EMG_{FT} for the control visit given the contrasting fitness levels of the 2 groups. Therefore, we performed an independent-samples t-test, which indicated that the EMG_{FT} was significantly different between the 2 groups for the control visit (healthy subjects: 27 ± 2 W vs. elite runners: 38 ± 3 W; $p = 0.007$). Therefore, we used the EMG_{FT} value from the control visit as a covariate.

Before performing the analysis of covariance (ANCOVA), we tested the homogeneity of regression assumption, which was met ($p = 0.317$). Thereafter, we used the EMG_{FT} value from the control visit as a covariate in the ANCOVA to determine mean differences between EMG_{FT} values after the Thorstensson test. The results revealed significant mean differences for the corrected marginal mean values (healthy subjects: 25 ± 1 W vs. elite runners: 36 ± 1 W; $p < 0.001$).

We also wanted to determine, within each group, whether the EMG_{FT} was influenced by the Thorstensson test compared with the control visit. Therefore, a 2 (group: elite runners or healthy subjects) × 2 (visit: control and Thorstensson) mixed factorial ANOVA with EMG_{FT} as the dependent variable was performed. The analyses revealed a significant group × visit interaction [$F(1, 15) = 8.73$; $p = 0.010$]. Moreover, there was a significant main effect for visit [$F(1, 15) = 6.49$; $p = 0.022$] and a significant main effect for group [$F(1, 15) = 23.72$; $p < 0.001$]. For the significant interaction, the model was decomposed, with a Bonferroni correction, to determine whether or not there were mean differences for EMG_{FT} between visits within each group. The results indicated no mean differences in the EMG_{FT} for the elite runners (control: 38 ± 2 W vs. Thorstensson: 39 ± 2 W; $p = 0.771$). For the healthy subjects, however, the results indicated a significant mean difference in the EMG_{FT} between visits (control: 27 ± 3 W vs. Thorstensson: 21 ± 2 W; $p = 0.002$).

We also wanted to determine whether or not there were changes in the slope coefficient for the exercise intensity vs. normalized EMG amplitude between the 2 visits within each group. As shown in Figure 1 (panel A), for the healthy subjects, there were no significant differences in the slope coefficient between the 2 visits. However, for the elite runners, the slope of the regression line after performing the Thorstensson test was significantly higher than the control condition (Figure 1, panel B).

Discussion

The principal finding of the current investigation was that pre-exhaustion exercise performed before the EMG_{FT} test did not influence neuromuscular response to incremental single-leg knee-extensor ergometry in a group of elite runners. Interestingly, we found that when the slopes of the normalized EMG amplitude vs. normalized exercise intensity relationship were compared between the 2 testing visits (control vs. Thorstensson), there was a significantly higher rates of increase in the normalized EMG amplitude in the

Thorstensson visit vs. control. Conversely, we found that in a group of healthy subjects, that were not elite athletes, our pre-exhaustion protocol resulted in significantly reducing the EMG_{FT} compared with the control visit. To the best of our knowledge, this is the first investigation to show divergent responses to neuromuscular activity during incremental exercise after a pre-exhaustion exercise.

Studies on the role of neuromuscular response using a pre-exhaustion model on subsequent exercise are equivocal. For example, Layec et al. (21) examined the role of high-intensity knee-extension exercise on muscle recruitment in a group of health subjects. The investigators reported that the EMG amplitude-work relationship remained constant during the second workbout, but in the initial phase was significantly higher when compared with the first workbout. Therefore, Layec et al. (21) concluded that heavy exercise facilitates recruitment of motor units during the early phase of the second workbout (21). Brennecke et al. (6) determined potential changes in the EMG amplitude for the pectoralis major, anterior deltoids, and long head of the triceps brachii for bench press exercise. In their experimental condition, subjects performed dumbbell fly exercise before performing bench press exercise at a load corresponding to their 10 repetition maximum, whereas in the control condition, subjects performed the bench press exercise only (6). When the EMG amplitude was normalized to the maximal voluntary isometric activation, the results indicated no significant mean differences in the EMG signal between the control and experimental conditions for the pectoralis major and anterior deltoid muscles (6). There was, however, a significant reduction in the EMG signal between the 2 conditions for the triceps brachii muscle (6). The investigators suggested that the observed increase may be, in part, due to tonic muscle control (6). Using various physiological parameters, Soares et al. (33) compared and contrasted traditional exercise order with pre-exhaustion on muscle activation and performance in trained men. To this end, each subject performed the bench press exercise under 3 conditions (pretest, traditional, and pre-exhaustion) (33). Soares et al. (33) found that the pre-exhaustion condition significantly reduced the number of repetitions completed compared with the other 2 conditions (33). Moreover, the investigators reported that, regardless of the condition, the normalized EMG amplitude was significant higher in the last repetition vs. the first repetition (33). These results suggest that, for bench press exercise, the order of exercise can influence functional outcomes (i.e., repetitions completed), but may not be explained by physiological measurements such as neuromuscular response (33).

In this study, we found no significant group $\times$ visit interaction for maximal power output, absolute and relative heart rate at end of exercise, and maximal leg rating of perceived exertion. However, when collapsed across visits, we found that elite runners achieved a significantly higher power output with a corresponding lower end exercise heart rate than the healthy subjects. This difference is to be expected given that the single-leg knee-extensor ergometry is an endurance test albeit isolated to the quadriceps femoris muscles. To determine whether or not the Thorstensson test influenced the subsequent estimated EMG_{FT} between the 2 groups, we first had to account for the initial mean differences between the 2 groups for the estimated EMG_{FT} during the control visit. This initial difference was expected given the fitness levels of the 2 groups (healthy subjects vs. elite runners). Once this correction was made, using ANCOVA, the results revealed that the Thorstensson test performed before the incremental single-leg knee-extensor ergometry significantly reduced the estimated EMG_{FT} in the healthy subjects by ~30% compared with the elite runners. Moreover, we found that when the estimated EMG_{FT} values between the 2 visits (control and Thorstensson test) were compared within each group, there was a significant reduction in the estimated mean EMG_{FT} for the healthy subjects group. This pattern of responses was not exhibited in the elite runners group because the Thorstensson test did not influence their estimated mean EMG_{FT}. The results of this study, therefore, suggest that pre-exhaustion exercise as operationally defined in the current investigation significantly reduced the estimated EMG_{FT} in healthy subjects only.

The divergent responses to the pre-exhaustion exercise on the estimated EMG_{FT} between the healthy subjects and the elite runners may, in part, be due to characteristics of the rectus femoris muscle. Studies indicate that biarticular muscles such as the rectus femoris muscle may contribute to the muscular fatigue in elite runners (14,15,35). Although there is continued debate, investigators have examined the role of muscle coactivation between agonist-antagonist muscles such as the rectus femoris and biceps femoris to provide insight into running economy (28). Generally, type I fibers are more fatigue resistant relative to type IIa and IIx fibers (16). Goswami et al. (14) examined the rectus femoris muscles of sprinters and long distance runners. The investigators found that differences in the EMG signal between the 2 groups for maximal isometric knee extension was due to differences in fiber type compositions, albeit the investigators did not perform muscle biopsies of the rectus femoris muscle (14). That is, sprinters have a higher proportion of type II myosin heavy chain isoform, whereas elite long-distance runners have a higher proportion of type I myosin heavy chain isoform (3,5). Methenitis et al. (26) compared and contrasted the vastus lateralis muscle between 4 groups (sedentary, endurance runners, power-trained, and strength-trained) of young men. Using muscle biopsies from the vastus lateralis muscle, the investigators found significant mean differences between the 4 groups for muscle fiber composition (26). Specifically, they reported that for the endurance group, the percentage of cross-sectional area for type I fibers was significantly higher in the endurance group compared with the other 3 groups (26). Moreover, they reported that the percentage of type II fibers was lowest in the endurance group (26). Although we did not determine myosin heavy chain isoform in the current study, it is feasible to conclude that the elite runners had significantly higher type I myosin heavy chain isoform in their thigh muscles compared with the healthy subjects. Contessa et al. (8) stated, "…the degree of motor unit firing adaptations during fatigue varies among subjects, as the mechanical and biochemical characteristics of muscles may differ among individuals." (p.1585). Nene et al. (29) examined the patterns of responses for the EMG signal during gait in able-bodied subjects for the quadriceps femoris muscles. The investigator concluded that the rectus femoris during walking was active during the stance-to-swing transition, but that as the pace increased, the EMG activity increased during the swing-to-stance transition (29). The exercise mode used in current study is the single-leg knee-extensor ergometry, which isolates the quadriceps femoris muscles while concomitantly minimizing cardiovascular and respiratory responses to exercise (9,13,24,25,32). Moreover, Richardson et al. (32) reported that the rectus femoris muscle had the highest activation compared with the vastus lateralis, vastus medialis, and vastus intermedius muscles for single-leg knee-extensor ergometry. In addition, Noble et al. (30) reported that the EMG amplitude in the rectus femoris muscle was significantly higher during single-leg knee-extensor ergometry vs. single-leg cycle ergometry. Taken together, these factors may explain, in part, why the Thorstensson test did not influence neuromuscular fatigue in the elite runners.

Practical Applications

In the current study, we used a single 50-repetition isokinetic muscle action exercise to prefatigue the quadriceps femoris muscles before having subjects perform an incremental exercise test that isolates the same muscle group. As a result, subjects who were not elite athletes exhibited reductions in their neuromuscular fatigue threshold. Therefore, in this group of subjects, their estimated EMG_{FT} was compromised, whereas with the elite runners, we did not see such a response. The application of these findings resides in understanding that individuals at different fitness levels (ranging from beginner to elite) will response differently to workloads of exercise performed before the main competition or race.

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