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Application of the neuromuscular fatigue threshold treadmill test to muscles of the quadriceps and hamstrings

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Abstract

Purpose: The purposes of the present study were: (1) to determine whether the physical working capacity at the fatigue threshold (PWCFT) model that has been used for estimating the onset of neuromuscular fatigue in the vastus lateralis (VL) during incremental treadmill running could also be applied to the vastus medialis (VM), biceps femoris (BF), and semitendinosus (ST) muscles; and (2) if applicable, to compare the running velocities associated with the PWCFT among these muscles.

Methods: Eleven subjects (age 21.7 ± 1.8 years) performed an incremental treadmill test to exhaustion with electromyographic signals recorded from the VL, VM, BF, and ST.

Results: The results indicated there were no significant (p > 0.05) mean differences in the running velocities associated with the PWCFT for the VL (14.4 ± 2.0 km/h), VM (14.3 ± 1.9 km/h), BF (13.8 ± 1.8 km/h), and ST (14.7 ± 2.3 km/h). In addition, there were significant inter-correlations (r = 0.68–0.88) among running velocities associated with the PWCFT of each muscle. Individual results also indicated that 9 of the 11 subjects exhibited identical PWCFT values for at least 3 of the 4 muscles, but there were no uniform patterns for any intra-individual differences.

Conclusion: The findings of the present study suggested that the PWCFT test is a viable method to identify neuromuscular fatigue in the quadriceps and hamstrings during incremental treadmill exercise and results in consistent PWCFT values among these muscles.

Keywords: EMG amplitude; Muscle activation; PWCFT

1. Introduction

The physical working capacity at the fatigue threshold (PWCFT) test of deVries et al. estimates the maximal power output that can be sustained for an extended period of time without evidence of neuromuscular fatigue during cycle ergometry. Specifically, the PWCFT test is based on within-stage increases in electromyographic (EMG) amplitude that reflect fatigue-induced increases in muscle activation (i.e., motor unit recruitment and firing rates) required to maintain the desired power output. It has been demonstrated that the PWCFT provides an accurate measurement of the highest non-fatiguing workload and results in consistent values among superficial muscles of the quadriceps (i.e., vastus lateralis (VL), rectus femoris (RF), and vastus medialis (VM)). Previous studies have used the PWCFT test to examine physiological factors associated with neuromuscular fatigue, to assess physical fitness and factors related to the degeneration of neuromuscular function in the elderly, to prescribe exercise training intensities, as well as to determine the effectiveness of exercise training programs and various nutritional supplements as ergogenic aids. Collectively, these findings illustrate that the PWCFT serves as a valid and reliable tool for estimating the onset of neuromuscular fatigue during cycle ergometry with athletic performance and clinical applications.

Recently, Camic et al. applied the PWCFT model used for cycle ergometry to incremental treadmill exercise to derive a new neuromuscular fatigue threshold test for running.
Utilizing the method of DeVries et al.\(^1\) and recording the EMG signal from the VL, Camic et al.\(^17\) reported that the PWC\(_{FT}\) model was able to identify fatiguing from non-fatiguing running velocities by examining the slope coefficients for the EMG amplitude vs. time relationships during each 2-min stage of an incremental treadmill test to exhaustion. Theoretically, the PWC\(_{FT}\) treadmill test estimates the fastest running velocity that can be sustained without progressive increases in muscle activation to compensate for the development of fatigue. It was also reported that the running velocity associated with the PWC\(_{FT}\) from the VL was significantly correlated \((r = 0.70)\) and occurred at the same running velocity \((14.0 \pm 2.3 \text{ km/h, mean } \pm \text{ SD})\) as the respiratory compensation point (RCP) \((14.0 \pm 1.8 \text{ km/h})\).\(^17\) These findings suggested that the PWC\(_{FT}\) determined from the VL during incremental treadmill exercise, like the RCP, (1) can be used to identify the boundary between the heavy and severe domains of exercise intensity, and (2) represents the maximal exercise intensity that can be achieved with oxygen uptake \((\text{VO}_2)\) and lactate still maintaining a steady state.\(^18\) It has recently been demonstrated, however, that the patterns (linear, quadratic, cubic) of responses for muscle activation (i.e., EMG amplitude) across exercise intensity (i.e., \(\text{VO}_2\)) are unique among muscles of the thigh and may be due to variations in muscle architecture, fiber type, or biomechanical differences.\(^19\) A number of other studies\(^20\)–\(^23\) have also reported differences in muscle-activation patterns between the quadriceps and hamstring groups with increases in running velocity or the development of fatigue. For example, Kyrolainen et al.\(^21\) showed that biarticular muscles (e.g., biceps femoris) exhibited changes in muscle activity across running phases with increases in velocities from 4.0 m/s to 8.5 m/s that were distinct from the activation patterns of monarticular muscles (e.g., VL). Thus, it is currently unknown whether the PWC\(_{FT}\) model is applicable to other muscles of the quadriceps as well as the hamstrings while running due to these variations in activation. Based on the anatomical and biomechanical differences that exist among these muscles, an assessment of their fatigue-induced activation strategies is warranted. Therefore, the purposes of the present study were: (1) to determine whether the PWC\(_{FT}\) model that has been used for estimating the onset of neuromuscular fatigue in the VL during incremental treadmill running could also be applied to the VM, biceps femoris (BF), and semitendinosus (ST) muscles; and (2) if applicable, to compare the running velocities associated with the PWC\(_{FT}\) among these muscles.

2. Methods

2.1. Subjects

Nine college-aged males \((\text{age} = 22.0 \pm 1.7 \text{ years}, \text{body mass} = 75.5 \pm 9.0 \text{ kg}, \text{height} = 178.2 \pm 5.8 \text{ cm})\) and 2 females \((20.5 \pm 2.1 \text{ years}, 58.7 \pm 3.1 \text{ kg}, 165.8 \pm 9.8 \text{ cm})\) volunteered to participate in this investigation. These subjects were selected based on their diverse running backgrounds, which included regular participation in recreational races (i.e., 5 km, 10 km) \((n = 3)\), marathons \((n = 4)\), ultramarathons \((n = 1)\), triathlons \((n = 1)\), collegiate track \((n = 1)\), and collegiate soccer \((n = 1)\). Each subject visited the laboratory on 2 occasions (separated by at least 48 h) and was instructed to: (1) maintain normal dietary habits and sleep patterns during the course of the study and (2) avoid exercise for 48 h, caffeine and alcohol for 24 h, and food intake for 3 h prior to each visit. The study was approved by the University of Wisconsin-La Crosse Institutional Review Board for Human Subjects, and all subjects completed a health history questionnaire and signed a written informed consent prior to testing.

2.2. Incremental Treadmill Tests

The first laboratory visit was structured as an orientation session to familiarize the subjects with the testing procedures (i.e., measurement of gas exchange and EMG while running on a treadmill). During the second laboratory visit, each subject performed an incremental test to exhaustion for the determination of PWC\(_{FT}\), RCP, and peak oxygen uptake \((\text{VO}_2\text{peak})\). The incremental treadmill test involved a standard warm-up of walking at 4.8–6.4 km/h for 4 min. Immediately following the warm-up, the test began at 9.7 km/h and increased 1.6 km/h every 2 min until volitional fatigue. This increment of 1.6 km/h was consistent with the original protocol\(^17\) and was selected for the practical purpose of estimating the PWC\(_{FT}\) across a wide range of running velocities in the diverse sample. The grade remained constant at 1.0\% during the test and was selected to represent the energy cost that is typically experienced by running outdoors.\(^24\)

2.3. EMG Measurements and Signal Processing

During the second laboratory visit, bipolar (10 mm center-to-center) wireless surface electrode sensors (Tringo Lab Wireless EMG System; Delsys, Natick, MA, USA) were placed on the right thigh over the VL, VM, BF, and ST muscles according to the recommendations of the SENIAM Project.\(^25\) Because of the lack of reliability of the EMG signal for the RF,\(^26\)\(^27\) this muscle was not examined. Prior to electrode sensor placement, the skin at each electrode site was dry-shaven, lightly abraded with gauze, and cleaned with alcohol. The EMG signals were amplified (gain: \(\times 1000\)) (Tringo Lab Wireless EMG System, bandwidth \(= 20–450 \text{ Hz}\), sampled at 2000 Hz, recorded continuously throughout the incremental test, and stored in a personal computer (Latitude E6540; Dell Inc., Round Rock, TX, USA) for subsequent analyses. All signal processing was performed using custom programs, which were written with MATLAB programming software (Version 8.2; Mathworks, Natick, MA, USA). The EMG signals were digitally bandpass filtered (fourth-order Butterworth) at 20–450 Hz.

2.4. Determination of PWC\(_{FT}\)

The PWC\(_{FT}\) values were determined using the model of DeVries et al.\(^1\) During each 2-min stage of the incremental treadmill test, six 10-s EMG samples were selected from the signal \((10–20, 30–40, 50–60, 70–80, 90–100, \text{ and } 110–120 \text{ s})\). The EMG amplitude (microvolts root mean
2.5. Measurements of Gas Exchange

All subjects wore a nose clip and breathed through a 2-way valve (2700, Hans Rudolph, Kansas City, MO, USA) during the incremental tests. Expired gas samples were collected and analyzed using a calibrated metabolic cart AEI Moxus and ventilatory parameters expressed as 30-s averages. Each subject was also fitted with a Polar Heart Watch system (Polar Electro, Lake Success, NY, USA) to monitor heart rate throughout the test. VO2peak was defined as the highest VO2 value in the last 30 s of the exercise test that met the criteria of Day et al.26 The test–retest reliability for VO2peak testing from our laboratory indicated that the intraclass correlation coefficient was $R = 0.95$, and the standard error of measurement29 (SEme) = 97 mL/min, with no significant ($p > 0.05$) mean difference between test and retest values. The RCP was determined by noninvasive gas-exchange measurements using the method of Beaver et al.30 For each subject, running velocities from the incremental treadmill test attained during the second laboratory visit were plotted against VO2 values, and the regression equation derived was used to determine the running velocity that corresponded to their RCP. The test–retest reliability for RCP testing from our laboratory indicated that the intraclass correlation coefficient was $R = 0.93$, and SEme = 103 mL/min, with no significant mean difference between test and retest values.

2.6. Statistical Analyses

Mean ± SD values were calculated for the PWCFT from the VL, VM, BF, and ST as well as RCP and VO2peak. For determination of PWCFT values, the relationships for EMG amplitude vs. time for each individual muscle and running velocity were examined using linear regression (IMB SPSS Statistics, Version 24; IMB Corp., Armonk, NY, USA). A 1-way repeated-measures ANOVA was also used to determine whether there were significant mean differences in running velocities among the PWCFT from each muscle and the RCP. Follow-up post hoc analyses included paired $t$ tests with Bonferroni correction. A 0-order correlation matrix was used to determine the relationships among the PWCFT from each muscle and the RCP. An $\alpha < 0.05$ was considered statistically significant for the 1-way repeated-measures ANOVA and all 0-order correlations.

3. Results

The results of the 1-way repeated-measures ANOVA and post hoc analyses indicated there were no significant ($p > 0.05$) differences among the running velocities associated with the VL PWCFT, VM PWCFT, BF PWCFT, ST PWCFT, and RCP (Table 1). In addition, the individual running velocities associated with the PWCFT were identical for all 4 muscles in 2 subjects, 3 of the 4 muscles in 7 subjects, and 2 of the 4 muscles in 2 subjects (Table 2). There were no consistent intra-subject patterns for the PWCFT values that distinguished the VL, VM, BF, and ST muscles (Table 2). Furthermore, there were significant ($p < 0.05$) 0-order correlations ($r = 0.60–0.88$) among the running velocities associated with the VL PWCFT, VM PWCFT, BF PWCFT, ST PWCFT, and RCP, except for the VM vs. RCP ($r = 0.52$) (Table 3).

Table 1

| Variable | Mean ± SD | Range |
|----------|-----------|-------|
| Age (year) | 21.7 ± 1.8 | 19.0–25.0 |
| Body mass (kg) | 73.9 ± 9.8 | 56.5–86.9 |
| Height (cm) | 176.8 ± 7.7 | 158.8–185.4 |
| Running volume (km/week) | 45.2 ± 39.9 | 6.4–160.9 |
| PWCFT (km/h) | | |
| VL | 14.4 ± 2.0 | 10.5–16.9 |
| VM | 14.3 ± 1.9 | 10.5–16.9 |
| BF | 13.8 ± 1.8 | 10.5–16.9 |
| ST | 14.7 ± 2.3 | 10.5–18.5 |
| RCP (km/h) | 14.5 ± 1.7 | 12.4–17.5 |
| RCP (L/min) | 4.08 ± 0.77 | 2.68–4.98 |
| VO2peak (L/min) | 4.78 ± 0.84 | 3.11–5.53 |
| VO2peak (mL/kg/min) | 64.4 ± 9.4 | 51.1–78.1 |

Notes: No significant differences ($p > 0.05$) were found among the running velocities associated with the PWCFT values for the vastus lateralis, vastus medialis, biceps femoris, or semitendinosus muscles as well as the RCP. Abbreviations: BF = biceps femoris; PWCFT = physical working capacity at the fatigue threshold; RCP = respiratory compensation point; ST = semitendinosus; VL = vastus lateralis; VM = vastus medialis; VO2peak = peak oxygen uptake.
Abbreviations: BF = biceps femoris; PWCFT = physical working capacity at the fatigue threshold; ST = semitendinosus; VL = vastus lateralis; VM = vastus medialis.

Table 2
Individual PWCFT values (km/h) for each muscle and subject.

| Subject code | VL  | VM  | BF  | ST  |
|--------------|-----|-----|-----|-----|
| 1            | 16.9| 16.9| 16.9| 16.9|
| 2            | 15.3| 15.3| 13.7| 15.3|
| 3            | 12.1| 10.5| 10.5| 10.5|
| 4            | 15.3| 15.3| 13.7| 15.3|
| 5            | 15.3| 12.1| 13.7| 13.7|
| 6            | 15.3| 15.3| 13.7| 15.3|
| 7            | 10.5| 13.7| 13.7| 13.7|
| 8            | 13.7| 13.7| 13.7| 13.7|
| 9            | 13.7| 13.7| 12.1| 12.1|
| 10           | 16.9| 16.9| 16.9| 16.9|
| 11           | 13.7| 13.7| 13.7| 16.9|

Table 3
Correlations among running velocities associated with the PWCFT of each muscle and respiratory compensation point.

|          | RCP       | VL    | VM    | BF    | ST    |
|----------|-----------|-------|-------|-------|-------|
| RCP      |           |       |       |       |       |
| VL       | 0.60*     |       |       |       |       |
| VM       | 0.52      | 0.70* |       |       |       |
| BF       | 0.80*     | 0.69* | 0.85* |       |       |
| ST       | 0.85*     | 0.68* | 0.84* | 0.88* |       |

* p < 0.05.

4. Discussion

One of the main findings of the present study was that the PWCFT model that has been used to estimate neuromuscular fatigue in the VL during incremental treadmill running was also applicable to other muscles of the quadriceps femoris (VM) and hamstring (BF, ST) groups. That is, the PWCFT method of deVries et al. was able to identify fatiguing from non-fatiguing running velocities during the incremental treadmill test by statistically examining the slope coefficient of the EMG amplitude vs. running velocity relationship of each stage for all muscles. Specifically, the EMG amplitude values at the velocities associated with fatigue increased across time for the VL (r = 0.74–0.99), VM (r = 0.78–0.99), BF (r = 0.76–0.98), and ST (r = 0.77–0.99) for all subjects, whereas the non-fatiguing running velocities resulted in non-significant relationships. These findings illustrated that the PWCFT test is a viable tool for estimating the running velocities associated with neuromuscular fatigue in individual muscles of the thigh. Previous studies using other methods have also identified neuromuscular fatigue in various lower-limb muscles based on increases in EMG amplitude during running. For example, Hanon et al. examined the difference in EMG amplitude values associated with 5–10 running bursts of activation at 0:45 (min:s) and 3:40 (min:s) of each 4-min stage for the VL, BF, gluteus maximus, RF, tibialis anterior, and gastrocnemius muscles during discontinuous, incremental treadmill running to exhaustion. In these studies, running velocities were defined as “fatiguing” if they exhibited significant increases in EMG amplitude at the end compared to the beginning of a stage. One of the major advantages of the PWCFT model used in the present study, however, is the evaluation of change in EMG amplitude across the entire stage, compared to only 5–10 running bursts of activation at 2 different time points. Thus, the use of the PWCFT model may provide greater insight into the evolution of fatigue during incremental treadmill running and may be less susceptible to outliers that exist among EMG activation bursts.

The findings of the present investigation also indicated that there were no significant mean differences in running velocities associated with the VL PWCFT (14.4 ± 2.0 km/h), VM PWCFT (14.3 ± 1.9 km/h), BF PWCFT (13.8 ± 1.8 km/h), and ST PWCFT (14.7 ± 2.3 km/h) (Table 1). In addition, there were significant inter-correlations for the PWCFT values that existed among all muscles (r = 0.68–0.88) (Table 3). Therefore, the identification of neuromuscular fatigue for the VL, VM, BF, and ST was associated with the same running velocity and was consistent among all muscles. These findings were similar with those of Housh et al. which indicated that the PWCFT occurred at the same power output for the superficial muscles of the quadriceps during incremental cycle ergometry. Using the PWCFT model and 30-W incremental stages, the authors reported: (1) no significant differences in the power output associated with neuromuscular fatigue for the VL (226 ± 58 W), VM (223 ± 58 W), and RF (203 ± 54 W), and (2) significant inter-correlations (r = 0.78–0.92) among the muscles. In conjunction, the findings of the present study and those of Housh et al. suggested that the PWCFT serves as a reliable tool to identify neuromuscular fatigue during incremental treadmill running and cycle ergometry. It is important to note, however, that the running velocities associated with the PWCFT in the current investigation were identical for: (1) all 4 muscles in 2 subjects, (2) 3 muscles for 7 subjects, and (3) 2 muscles for 2 subjects (Table 2). As proposed by Housh et al., it is possible that these intra-subject differences in the PWCFT among muscles may be due to variations in fiber-type distribution, training status or protocols, and biomechanical differences. Thus, the current findings suggested that an examination into intra-subject variability in the PWCFT can be used to identify muscle imbalances among the quadriceps and hamstring groups during running as well as to determine individual training strategies for athletes. For example, the potential uses for PWCFT identification in various muscles of interest include: (1) to determine the effectiveness of training programs through pre- and post-assessments, (2) to prescribe exercise training intensities (i.e., running velocities) based on %PWCFT, (3) to assess the impact of running-form adjustments on fatigue-related aspects of muscle activation, and (4) to assess the rehabilitative progress in recovering from injury. It is also possible that the PWCFT protocol could be modified to identify muscle fatigue across differing velocities and grades, depending on performance requirements. In particular, deVries et al. suggested that the PWCFT treadmill test would...
be customized for the elderly by using slower velocities to assess fatigue-related aspects of neuromuscular function during walking. Therefore, the PWCFFT treadmill test has practical applications that can be potentially useful in both athletic and special populations.

The PWCFFT values for each muscle (VL = 14.4 ± 2.0 km/h, VM = 14.3 ± 1.9 km/h, BF = 13.8 ± 1.8 km/h, and ST = 14.7 ± 2.3 km/h) also occurred at the same running velocity as the RCP (14.5 ± 1.7 km/h) (Table 1). In addition, there were significant inter-correlations among the PWCFFT values for each muscle vs. the RCP (r = 0.60–0.88), except the VM (r = 0.52) (Table 3). As described previously, the relationships among neuromuscular (PWCFFT) and ventilatory-based thresholds (ventilatory threshold and RCP) provide information related to the practical applications and validity of the PWCFFT treadmill test. That is, the running velocity associated with neuromuscular fatigue in muscles of the thigh, like the RCP, demarcates the border between the heavy and severe domains of exercise intensity and, thus, represents the maximal running velocity that can be maintained for an extended period of time with VO2 and lactate still reaching a steady state. In particular, it has been established that continuous exercise above the heavy-intensity domain results in VO2 and lactate values that do not stabilize, and VO2 reaches its maximum. These findings offer physiological validation that the PWCFFT is an accurate estimate of the highest non-fatiguing running velocity. Practical validation of the PWCFFT model during treadmill exercise through constant runs to exhaustion at, below, and above the estimated PWCFFT, however, has not been examined.

5. Conclusions

In summary, the findings of the present investigation illustrated that the PWCFFT that has previously been used to identify the onset of neuromuscular fatigue in the VL is also applicable to other muscles of the thigh (i.e., VM, BF, and ST) during incremental treadmill running. The non-significant mean differences and significant correlations among the running velocities of the VL PWCFFT, VM PWCFFT, BF PWCFFT, and ST PWCFFT suggested that this neuromuscular fatigue threshold results in consistent estimates across muscles of the quadriceps femoris and hamstring groups and may be used to identify muscle imbalances as well as to determine individual training strategies for athletes. In addition, the development of fatigue in these muscles as indicated by the PWCFFT coincided with the running velocity associated with the RCP. These findings provide physiological validation for the PWCFFT model during incremental treadmill running.

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Authors’ Contributions

CLC conceived the study design, data collection, and analysis and drafted the manuscript; AJK assisted with study design and carried out the electromyographic analyses; TAV, ECH, and EAE were involved with study design and coordination, data collection and analysis. All authors have read and approved the final manuscript, and agreed with the order of presentation of the authors.

Competing Interest

The authors declare that they have no competing interests.

References

1. deVries HA, Housh TJ, Johnson GO, Evans SA, Tharp GD, Housh DJ, et al. Factors affecting the estimation of physical working capacity at the fatigue threshold. Ergonomics 1990;33:25–33.
2. Briscoe MJ, Forbach MS, Trifan E, Malek MH. Validating the EMGFT from a single incremental cycling test. Int J Sports Med 2014;35:266–70.
3. Housh TJ, deVries HA, Johnson GO, Evans SA, Housh DJ, Stout JR, et al. Neuromuscular fatigue thresholds of the vastus lateralis, vastus medialis and rectus femoris muscles. Electromyogr Clin Neurophysiol 1996;36:247–55.
4. deVries HA, Tichy MW, Housh TJ, Smyth KD, Tichy AM, Housh DJ. A method for estimating physical working capacity at the fatigue threshold. Ergonomics 1987;30:1195–204.
5. Housh TJ, deVries HA, Johnson GO, Evans SA, McDowell S. The effect of ammonium chloride and sodium bicarbonate ingestion on the physical working capacity at the fatigue threshold. Eur J Appl Physiol Occup Physiol 1991;62:189–92.
6. Housh TJ, deVries HA, Johnson GO, Evans SA, Tharp GD, Housh DJ, et al. The effect of glycogen depletion and supercompensation on the physical working capacity at the fatigue threshold. Eur J Appl Physiol Occup Physiol 1990;60:391–4.
7. deVries HA, Bradowicz GR, Robertson LD, Svoboda MD, Schendel JS, Tichy AM, et al. Estimating physical working capacity and training changes in the elderly at the fatigue threshold (PWCFTT). Ergonomics 1989;32:967–77.
8. Emerson NS, Fukuda DH, Stout JR, Robinson 4th EH, McCormack WP, Scanlon TC, et al. Physical working capacity at fatigue threshold (PWCFTT) is associated with sarcopenia-related body composition and measures of functionality in older adults. Arch Gerontol Geriatr 2014;59:300–4.
9. Stout JR, Fragała MS, Hoffman JR, Robinson 4th EH, McCormack WP, Townsend JR, et al. C-terminal agrin fragment is inversely related to neuromuscular fatigue in older men. Muscle Nerve 2015;51:132–3.
10. Casaburi R, Storer TW, Sullivan CS, Wasserman K. Evaluation of blood lactate elevation as an intensity criterion for exercise training. Med Sci Sports Exerc 1995;27:852–62.
11. Jenkins ND, Buckner SL, Baker RB, Bergstrom HC, Cochrane KC, Weir JP, et al. Effects of 6 weeks of aerobic exercise combined with conjugated linoleic acid on the physical working capacity at the fatigue threshold. J Strength Cond Res 2014;28:2127–35.
12. Camic CL, Housh TJ, Zuniga JM, Hendrick RC, Mielke M, Johnson GO, et al. Effects of arginine-based supplements on the physical working capacity at the fatigue threshold. J Strength Cond Res 2010;24:1306–12.
13. Miramonti AA, Stout JR, Fukuda DH, Robinson 4th EH, Wang R, La Monica MB, et al. Effects of four weeks of high-intensity interval training and β-hydroxy-β-methylbutyric free acid supplementation on the onset of neuromuscular fatigue. J Strength Cond Res 2016;30:626–34.
14. Stout JR, Cramer JT, Zoeller RF, Torok D, Costa P, Hoffman JR, et al. Effects of β-alanine supplementation on the onset of neuromuscular fatigue and ventilatory threshold in women. Amino Acids 2007;32:381–6.
15. Stout JR, Graves SB, Cramer JT, Goldstein ER, Costa PB, Smith AE, et al. Effects of creatine supplementation on the onset of neuromuscular fatigue threshold and muscle strength in elderly men and women (64–86 years). J Nutr Health Aging 2007;11:459–64.
16. Zak RB, Camic CL, Hill EC, Monaghan MM, Kovacs AJ, Wright GA. Acute effects of an arginine-based supplement on neuromuscular, ventilatory, and metabolic fatigue thresholds during cycle ergometry. *Appl Physiol Nutr Metab* 2015;40:379–85.

17. Camic CL, Kovacs AJ, Enquist EA, VanDusseldorp TA, Hill EC, Calantoni AM, et al. An electromyographic-based test for estimating neuromuscular fatigue during incremental treadmill running. *Physiol Meas* 2014;35:2401–13.

18. Gaesser GA, Poole DC. The slow component of oxygen uptake kinetics in humans. *Exerc Sport Sci Rev* 1996;24:35–71.

19. Camic CL, Kovacs AJ, Enquist EA, VanDusseldorp TA, Hill EC. Muscle activation of the quadriceps and hamstrings during incremental running. *Muscle Nerve* 2015;52:1023–9.

20. Hanon C, Thépaut-Mathieu C, Vandewalle H. Determination of neuromuscular fatigue in elite runners. *Eur J Appl Physiol* 2005;94:118–25.

21. Kyröläinen H, Avela J, Komi PV. Changes in muscle activity with increasing running speed. *J Sports Sci* 2005;23:1101–9.

22. Nummela AT, Heath KA, Paavolainen LM, Lambert MI, St Clair Gibson A, Rusko HK, et al. Fatigue during a 5-km running time trial. *Int J Sports Med* 2008;29:738–45.

23. Hanon C, Thépaut-Mathieu C, Hauswirth C, Le Chevalier JM. Electromyogram as an indicator of neuromuscular fatigue during incremental exercise. *Eur J Appl Physiol Occup Physiol* 1998;78:315–23.

24. Jones AM, Doust JH. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. *J Sport Sci* 1996;14:321–7.

25. Hermens HJ, Freriks B, Merletti R, Stegeman D, Blok J, Rau G, et al. SENIAM European recommendations for surface electromyography: results of the SENIAM project. Enschede, the Netherlands: Roessingh Research and Development; 1999.p.15–55.

26. Rainoldi A, Bullock-Saxton JE, Cavarretta F, Hogan N. Repeatability of maximal voluntary force and of surface EMG variables during voluntary isometric contraction of quadriceps muscles in healthy subjects. *J Electromyogr Kinesiol* 2001;11:425–38.

27. Rainoldi A, Melchiorri G, Caruso I. A method for positioning electrodes during surface EMG recordings in lower limb muscles. *J Neurosci Methods* 2004;134:37–43.

28. Day JR, Rossiter HB, Coats EM, Skasick A, Whipp BJ. The maximally attainable VO2 during exercise in humans: the peak vs. maximum issue. *J Appl Physiol (1985)* 2003;95:1901–7.

29. Harvill LM. An NCME instructional module on standard error of measurement. *Educ Meas* 1991;10:33–41.

30. Beaver WL, Wasserman K, Whipp BJ. A new method for detecting anaerobic threshold by gas exchange. *J Appl Physiol (1985)* 1986;60:2020–7.

31. Guffey DR, Gervasi BJ, Maes AA, Malek MH. Estimating electromyographic and heart rate fatigue thresholds from a single treadmill test. *Muscle Nerve* 2012;46:577–81.