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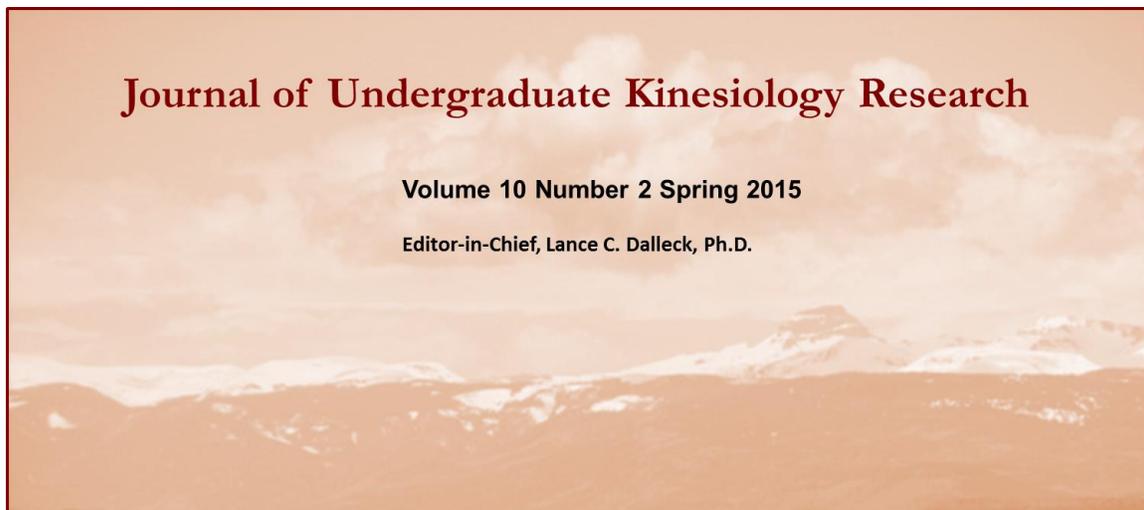
THE EFFECTS OF MUSCLE CROSS-SECTIONAL AREA ON THE PHYSICAL WORKING CAPACITY AT THE FATIGUE THRESHOLD

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ABSTRACT

Barry MB, Zuniga JM, Brown MM, Garnett WM, Hadden ZV, Nguyen PK, Supplee GA, Svoboda CJ. The Effects of Muscle Cross-sectional Area on the Physical Working Capacity at the Fatigue Threshold. *Journal of Undergraduate Kinesiology Research* 2015;10(2):20-30. **Purpose:** The purpose of this study was to examine the effects of quadriceps cross-sectional area (CSA) of the dominant quadriceps muscle in the assessment of the physical working capacity at the fatigue threshold (PWC_{FT}) during incremental cycle ergometry. **Methods:** Eighteen adults (9 men and 9 women; mean age ± SD = 20.5 ± 1.04 yr; mean body weight ± SD = 73.9 ± 18.2 kg; mean height ± SD = 172.3 ± 11.5 cm; mean dominant quadriceps CSA ± SD = 68.7 ± 14.5 cm^2) performed an incremental cycle ergometry test to exhaustion while the electromyographic (EMG) signals were recorded from the vastus lateralis (VL) muscles. Fatiguing and non-fatiguing power outputs were differentiated by examining the slope coefficients for the EMG amplitude versus time relationship at each power output throughout the incremental cycle ergometry test. Quadriceps CSA was estimated from an equation. Subjects were divided into groups of small quadriceps CSA (57.3 ± 10.0 cm^2) and large quadriceps CSA (80.0 ± 7.6 cm^2). **Results:** Independent t-test results indicated no significant mean differences between the PWC_{FT} for the large and small quadriceps CSA groups (p=0.456). **Conclusion:** The findings of the study suggest that muscle CSA may not have a significant effect on

the assessment of the PWC_{FT}, and therefore that PWC_{FT} may be a determinant of neuromuscular fatigue independent of muscle CSA. Future research could explore the contributions of muscle fiber-type predominance to CSA and PWC_{FT} and provide more conclusive evidence relating these variables.

Key Words: Exercise, Physiology, Electromyography, Cycle Ergometry

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INTRODUCTION

Electromyography (EMG) has been shown to be an acceptable method for non-invasively assessing the contractile activity of working muscles during fatiguing bouts of exercise (16, 21). The EMG signal records the sum of muscle action potentials as a waveform comprised of amplitude and frequency domains. The amplitude of the EMG signal represents the level of muscle activation, including motor unit recruitment and firing rates, while the frequency domain is primarily reflective of muscle fiber conduction velocity. Fatigue induced by static or dynamic exercise bouts is typically characterized by time-dependent increases in surface EMG signal amplitude and corresponding decreases in EMG mean power frequency (MPF) (36).

Based on the fatigue-induced changes in these signal domain parameters, previous investigations (4, 17, 22, 34) have utilized the surface EMG signal to determine the neuromuscular fatigue threshold (NMFT). Specifically, the NMFT is derived from calculation of the physical working capacity of the muscle at the fatigue threshold (PWC_{FT}) using the EMG amplitude versus time relationship. By utilizing the PWC_{FT} test and the EMG amplitude fatigue curves, the rate of increase in the EMG amplitude can provide information in regards to the fatigue-induced recruitment of additional motor units (4). From the determination of the PWC_{FT} test, the highest power output a subject can maintain without indication of neuromuscular fatigue can be approximated (6).

Assessment of the PWC_{FT} has been used in previous investigations to examine the relationship between maximal treadmill velocity and neuromuscular fatigue (3), determine parameters of physical fitness (7), and study the efficacy of dietary supplements (15). Such findings have suggested that PWC_{FT} may be an effective method of assessing neuromuscular function and differentiating exercise intensity.

Among these findings, there is little conclusive research on the direct relationship between anthropometric estimates of muscle cross-sectional area (CSA) and the PWC_{FT} as assessed by surface EMG. Quantification of the mid-thigh CSA has been employed in nonclinical settings to compare athletic and non-athletic populations, predict muscle strength, and explore the outcomes of various interventions on hypertrophy and atrophy. In particular, quadriceps CSA is obtained via insertion of mid-thigh circumference and anterior thigh skinfold measurements into regression equations that have been validated against alternative methods for accuracy (16).

While it is largely accepted that a significant linear relationship exists between muscle strength and corresponding CSA as measured by computed tomography (CT), ultrasound, and contiguous

magnetic resonance imaging (MRI) methods (22, 23), researchers have cautioned that muscle fiber type distribution should be considered as a source of variability (23). For instance, Linssen et al. (20) demonstrated that type I fibers showed less fatigability than the type II variety during isometric exercise tests of the quadriceps femoris, which was reflected by a slight increase of the surface EMG amplitude compared to recordings of subjects with less type I predominance. Other studies have suggested that muscular hypertrophy will cause a decrease in the ratio of strength to CSA if the stress within active muscle fibers remains constant, resulting in an inverse relationship between CSA and the ratio of strength to CSA (36).

In light of the scarce research on this topic, the purpose of the present investigation was to examine the effects of estimated quadriceps CSA on the PWC_{FT}. Based on previous studies (20, 36), it was hypothesized that greater estimated quadriceps CSA would elicit a decreased signal amplitude and lower associated power output, or PWC_{FT}, delaying the onset of fatigue.

METHODS

Subjects
Eighteen adults (9 men and 9 women; mean age ± SD = 20.5 ± 1.04 yr; mean body weight ± SD = 73.9 ± 18.2 kg; mean height ± SD = 172.3 ± 11.5 cm; mean dominant quadriceps CSA ± SD = 68.7 ± 14.5 cm^2) volunteered to participate in the investigation. The study was approved by the University Institutional Review Board for Human Subjects. All subjects completed a health history questionnaire and signed an informed consent document before testing.

Instrumentation
Estimation of Quadriceps Cross Sectional Area
An estimate of the quadriceps CSA was obtained using an equation developed by Housh et al. (13):

Quadriceps CSA (cm^2) = (2.52 x mid-thigh circumference in cm) - (1.25 x anterior thigh skinfold in mm) - 45.13
R (multiple correlation coefficient) = 0.86
SEE (standard error of estimate) = 5.2 cm^2

The quadriceps circumferences of the dominant and non-dominant thighs were taken using a standard measuring tape (Gulick Tape II, Moberly, Missouri). The distance (cm) around the thigh, midway between the hip (inguinal fold) and knee joints (superior border of the patella), was measured three times. The average of the three circumferences was used for analyses. Quadriceps skinfolds were measured using a skinfold caliper (Lange, Creative Health Process Products Inc., Ann Arbor, Michigan). A vertical fold (mm) on the anterior aspect of the thigh, midway between the inguinal fold and knee joints, was measured three times. The average of the three trials was utilized in the analyses.

Maximal Cycle Ergometry Test
An orientation session was performed to familiarize the subjects with the protocol for the maximal cycle ergometer test during which each subject pedaled (70 rev·min^{-1}) for 2 min at 50 and 75 W.

Twenty-four to forty-eight hours following the orientation session, each subject performed an incremental test to exhaustion on a Calibrated Lode electronically-braked cycle ergometer (Lode Corival, Groningen, Netherlands) at a pedal cadence of 70 rev·min^{-1}. The seat was adjusted so that the subjects' legs were at near full extension during each pedal revolution. Each subject was fitted with a nose clip and breathed through a two-way valve (Hans Rudolph 2700 breathing valve, Kansas City, Missouri). Expired gas samples were collected and analyzed using a calibrated True Max 2400 metabolic measurement system (Parvo Medics, Sandy, Utah) with oxygen (O_2), carbon dioxide (CO_2), and ventilatory parameters expressed as 30-s averages. Heart rates were monitored with a Polar Heart Watch system (Polar Electro Inc., Lake Success, New York). The metabolic cart was calibrated prior to each test. The subjects began pedaling at 50 W and the power output was then increased by 25 W every 2 min throughout the test until volitional exhaustion or when the subject could no longer maintain a pedal cadence of 70 rev·min^{-1} despite strong verbal encouragement. Peak maximal oxygen consumption (VO_{2peak}) was defined as the highest maximal oxygen consumption (VO_{2max}) value in the last 30 s of the test if the subject met at least two of the following three criteria: (a) 90 % of age-predicted maximum heart rate (220-age), (b) respiratory exchange ratio > 1.10, and (c) a plateau of oxygen uptake ($\leq$ 150 ml · min^{-1} in VO_2 over the last 30 s of the test) (4). At the completion of the test, the subjects were allowed to cool down for as long as they liked. The test-retest reliability for VO_{2peak} testing from the laboratory indicated the intraclass correlation coefficient (ICC) was R = 0.95, with no significant mean difference between test and re-test values (35).

EMG Measurements
A bipolar surface EMG electrode (circular 4 mm diameter, silver/silver chloride, Biopac Systems, Inc., Santa Barbara, CA) arrangement was placed on the vastus lateralis (VL) of both right and left quadriceps (20 mm interelectrode distance) (35). The electrodes were aligned parallel to the muscle fibers of the VL in compliance with SENIAM Project recommendations. A reference line was drawn from the lateral border of the patella to the anterior superior iliac crest (35). The electrodes were positioned 5 cm lateral from one-third of the distance of this established reference line. A goniometer (Smith & Nephew Rolyan, Inc., Menomoncee Falls, Wisconsin) was utilized to orient the electrodes at a 20° angle to the reference line to estimate the pennation angle of the VL. Before placing the electrodes, the skin at each site was shaved, carefully abraded, and sanitized with alcohol. The reference electrode was placed over the tibial tuberosity. Interelectrode impedance was less than 2000 Ω. The EMG signal was amplified (gain: x1000) using differential amplifiers (EMG 100, Biopac Systems, Inc., Santa Barbara, California, bandwidth= 10-500 Hz) (36).

Procedures
Signal Processing
The raw EMG signals were digitized at 1000 Hz and stored in a personal computer (Inspiron 1520, Dell, Inc., Round Rock, Texas) for subsequent analysis. All signal processing was performed using custom programs written with Lab VIEW programming software (version 8.5, National Instruments, Austin, Texas). The EMG signals were bandpass filtered (fourth order Butterworth) at 10–500 Hz and 5–100 Hz, respectively.

Determination of PWC$_{FT}$

The PWC$_{FT}$ values were determined using the model of deVries et al. (6) for the amplitude domain of the EMG signal. During each 2 min stage of the incremental cycle ergometer test to exhaustion, six 10-s EMG samples were recorded from the VL muscle. The EMG amplitude (microvolts root mean square, µVrms) values were calculated for each of the 10-s epochs (MP150, BIOPAC Systems Inc., Camino Goleta, California) and separately plotted across time for each power output of the test. The PWC$_{FT}$ was determined by averaging the highest power output that resulted in a non-significant (p > 0.05; single-tailed t -test) slope coefficient for the EMG amplitude versus time relationship, with the lowest power output that resulted in a significant (p < 0.05) positive slope coefficient as depicted in Figure 1 (4).
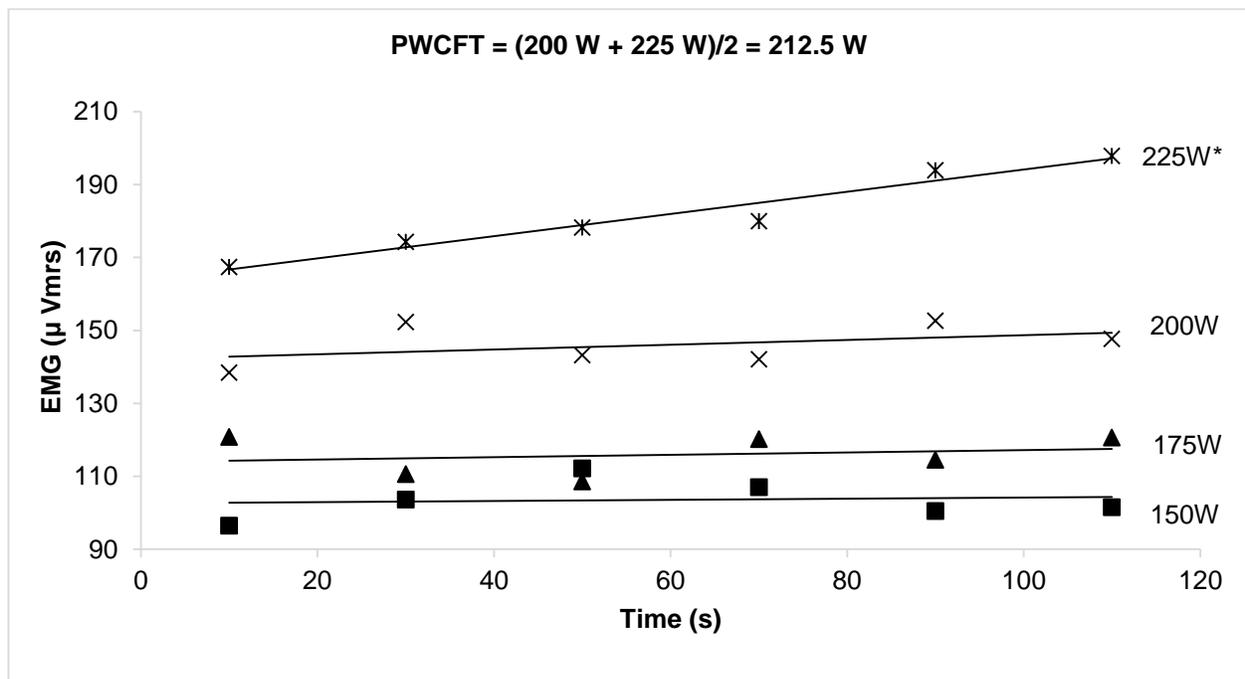
Figure 1: Illustration of the method used to estimate the physical working capacity at fatigue threshold (PWC$_{FT}$). The PWC$_{FT}$ in the current example (212.5 W) was determined by averaging the highest power output (200 W) that resulted in a non-significant (p > 0.05) slope coefficient for the EMG amplitude vs. time relationship, with the lowest power output (225 W) that resulted in a significant (p ≤ 0.05) positive slope coefficient. *Slope coefficient significantly greater than zero at p ≤ 0.05 (35).

Statistical Analyses

Mean, standard deviation, and range values were calculated for PWC$_{FT}$. The relationships for EMG amplitude versus time and power output for each subject were examined using linear regression (SPSS software program, Chicago, IL) (4). Independent t-tests were used to determine if there were significant mean differences in power outputs between the PWC$_{FT}$ for the large versus small quadriceps CSA (17). An alpha level of p < 0.05 was considered significant for all statistical analyses.

RESULTS

Table 1 provides mean, standard deviation, and range values for the demographic characteristics of the subjects, as well as the PWC$_{FT}$ for both large and small quadriceps CSA groups. Table 2

indicates PWC_{FT} and quadriceps CSA for all subjects. The results of the independent t-test indicated that there were no significant mean differences ($p < 0.05$) between the PWC_{FT} for the large quadriceps CSA (mean ± SD = 197.2 W ± 51.5 W) versus the small quadriceps CSA (mean ± SD = 177.7 W ± 51.5 W, Table 1) ($p = 0.456$).

Table 1: Physical characteristics and PWC_{FT} for large and small quadriceps CSA groups (n=18).

Variable	Mean
Age (years)	20.55 ± 1.04 (19-22)
Body Weight (kg)	73.91 ± 18.16 (51.71 - 112.49)
Height (cm)	172.26 ± 11.46 (157.48 - 193.04)
Small Group Quadriceps CSA (cm^2)	57.35 ± 10.01 (41.51 - 70.96)
Small Group PWC_{FT} (W)	177.77 ± 51.45 (125.0 - 287.0)
Large Group Quadriceps CSA (cm^2)	*80.02 ± 7.56 (70.95 - 92.97)
Large Group PWC_{FT} (W)	197.22 ±51.45 (112.5 - 300.0)

CSA = estimated muscle cross-sectional area
PWC_{FT} = EMG amplitude at fatigue threshold
*CSA was significant between the small and large groups ($p = 1.42E-8$).

Table 2: Individual and mean (SD) values for fatigue threshold (n=18).

Subject (gender)	Quadriceps CSA (cm^2)	PWC_{FT} (W) for Small CSA	Subject (gender)	Quadriceps CSA (cm^2)	PWC_{FT} (W) for Large CSA
1 (male)	41.51	212.5	10 (female)	70.95	112.5
2 (female)	47.14	162.5	11 (male)	71.2	212.5
3 (female)	50.24	137.5	12 (female)	74.8	162.5
4 (female)	53.43	137.5	13 (female)	74.99	175
5 (female)	57.62	162.5	14 (male)	81.41	225
6 (male)	63.39	125	15 (female)	82.81	212.5
7 (female)	63.47	162.5	16 (male)	83.66	200
8 (male)	68.38	212.5	17 (male)	87.38	300
9 (male)	70.96	287.5	18 (male)	92.97	175
Mean	57.35	177.77	Mean	80.02	197.22
SD	10.01	51.45	SD	7.56	51.45

CSA = estimated muscle cross-sectional area
PWC_{FT} = EMG amplitude at fatigue threshold

DISCUSSION

The purpose of this study was to examine the effects of dominant quadriceps CSA on the assessment of the PWC_{FT} during incremental cycle ergometry. Theoretically, the EMG PWC_{FT} is a measure of the highest power output attained during cycle ergometry without electromyographic indications of fatigue (i.e., no change in EMG PWC_{FT} over time). It was hypothesized that greater estimated quadriceps CSA would elicit decreased signal amplitude and lower associated power output, or PWC_{FT}, delaying the onset of neuromuscular fatigue. The independent t-test results indicated no significant ($p = 0.456$) mean differences between the PWC_{FT} for the large and small CSA

groups. In light of these findings, it may be reasoned that the PWC_{FT} is determinant of neuromuscular fatigue independent of muscle CSA.

As the measurement of quadriceps CSA takes no account of muscle fiber-type composition, it is plausible that the lack of a significant difference between muscle CSA and PWC_{FT} may be due to variable proportions of type I and type II muscle fibers in the research subjects (16). Previous investigations have indicated that type I muscle fiber predominance tends to elicit greater resistance to fatigability during bouts of exercise, while the type II variety is generally characterized by greater intrinsic strength, force generating capacity, and knee extension torque relative to a given CSA (18, 20, 23, 31). With necessary considerations for intersubject variability, studies further suggest that type I and type IIA muscle fibers, or slow oxidative and fast oxidative/glycolytic, respectively, are characterized by greater oxidative capacity and smaller size relative to type IIX or fast glycolytic muscle fibers (32). The greater hypertrophic tendencies of type IIX muscle fibers are demonstrated in findings by Nilwik et al. (28) that indicate differences in quadriceps muscle CSA - either associated with aging or in response to prolonged resistance training - are mainly attributed to differences in type II muscle fiber size.

Related investigations into the implications of muscle fiber type predominance have yielded conflicting results. A study by Beck et al. (2), for instance, concluded that differences in fiber type characteristics were not manifested in MMG-EMG spectrum MPF response patterns during fatiguing isometric leg extensions. Additionally, significant positive relationships between type I muscle fiber distribution and cycling efficiency have been identified in certain studies (5, 11, 12, 26) but not others (24, 29). In view of the conflicting literature, further research is needed to exclude muscle fiber type variability as an influential factor in the relationship between muscle CSA and neuromuscular fatigue.

Other investigations have examined muscle CSA independent of its component fiber-type predominance as it relates to fitness parameters. As previously mentioned, Maughan et al. (23) identified a significant (p<0.01) positive correlation between quadriceps CSA and muscle strength as measured by maximum voluntary isometric force, as well as a significant inverse relationship between muscle CSA and the ratio of strength to CSA. This finding confirmed a hypothesis originally derived by Alexander and Vernon (1975), which holds that an increased angle of pennation due to muscle hypertrophy will cause a decrease in the ratio of strength to anatomical CSA given constant stress within the fibers (1, 20). Thus, it appears there is a threshold at which the strength conferred through greater CSA is no longer optimal relative to muscle mass.

Given these findings, it could be reasoned that greater CSA and associated strength are most likely achieved at the expense of resistance to fatigue, while individuals with smaller CSA will generally demonstrate the reverse. All other elements of variability aside, these assumptions would explain the lack of a significant mean difference between the PWC_{FT} for those with large and small CSA due to the negation of each group's relative characteristics, and support PWC_{FT} as a measurement of fatigue independent of quadriceps CSA.

The possible limitations of this study involve the intrinsic characteristics of the research subjects. This study examined a subject population with large within-group variability in regards to cycling

experience and overall fitness. The use of a larger subject pool may yield more accurate data and less error. It is possible that the high standard deviation for PWC_{FT} ($\pm$ 51.45 W) may have led to non-significant results. Additionally, the noise generated by subjects shifting or adjusting on the bike during data collection could have affected the validity of the EMG amplitude signal. Future research could yield improvements with closer examination of the effects of muscle fiber type on PWC_{FT} or performance of this study with a larger subject population.

Our findings and those from previous studies (3, 6) suggest that using the EMG amplitude signal to determine PWC_{FT} provides useful information related to the recruitment of active muscle fibers (16). Other investigations have specifically shown the applications of PWC_{FT} to measurements of the aerobic power, muscular efficacy, and resistance to fatigue of the elderly (7). Such findings may guide the practice of physical therapists, exercise physiologists, and other health professionals in non-invasively assessing neuromuscular fatigue during dynamic muscle performance, examining functional limitations and physical disability independent of CSA, and prescribing appropriate rehabilitative or training programs to combat muscle atrophy or bilateral imbalances. The present study may also be applicable to athletes, the elderly, and other members of the general population experiencing altered morphology of the quadriceps muscle due to injury, aging, or extended bouts of cross training.

CONCLUSIONS

In conclusion, the findings of the present study indicated that the PWC_{FT} model of deVries et al. (6) can be used to assess the onset of neuromuscular fatigue during incremental cycle ergometry independent of CSA. The study found no significant ($p = 0.456$) mean differences between the PWC_{FT} for the large and small CSA groups, which suggests that muscle CSA may not have a significant effect on the assessment of the PWC_{FT}. Future research could explore the contributions of muscle fiber-type predominance to CSA and PWC_{FT} and provide more conclusive evidence relating these variables.

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