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Original Research Article

THE EFFECT OF DIFFERENT REGRESSION-BASED ALGORITHMS ON FREQUENCY BASED EMG FATIGUE

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Abstract

Purpose: The purpose of this study was to determine if there were significant differences between the electromyographic (EMG) mean power frequency at the fatigue threshold (MPF_{FT}) and D-max methods when assessing neuromuscular fatigue (NMF). **Methods:** Twenty-two adults (17 men, 5 women; mean ± standard (SD): age = 21.1 ± 2.8 years, body weight = 78.0 ± 12.7 kg, height = 177.4 ± 9.6cm) volunteered to participate in the investigation. Each participant performed an incremental cycle ergometry test to fatigue while EMG signals were measured from the vastus lateralis (VL) muscle. Mean, SD, and range values were calculated for the power outputs determined by the MPF_{FT} and D-max methods. The relationships for EMG frequency and power output for each participant were examined using linear regression (SPSS software program, Chicago, IL). An alpha level of $p \leq 0.05$ was considered significant for all statistical analyses. A paired dependent t-test was used to determine if there were significant mean differences in power outputs determined by the MPF_{FT} method (Mean ± SD; 161.9 ± 44.9 W) and D-max method (168.9 ± 36.6 W). **Results:** The results of the dependent t-test indicated that there were not significant mean differences ($p>0.05$) between the MPF_{FT} and D-max values ($p=0.29$). The zero-order correlation for the power outputs determined by the MPF_{FT} and D-max methods showed that the two methods were fairly correlated ($r=0.69$). **Conclusion:** The result of the present investigation suggests that the two regression-based algorithms can be used to calculate neuromuscular fatigue.

Key Words: electromyography, mathematical model, cycling test, neuromuscular fatigue

Introduction

Electromyography (EMG) is a technique that uses electrodes to measure electrical activity due to a muscle contraction[1]. By analyzing both amplitude and frequency, EMG can be used to determine the strength and number of motor units firing during physical activity. The amplitude is expressed in voltage over a specific period of time. The height of the EMG amplitude can give insight to changes in muscle fiber recruitment and firing rate. The EMG frequency is the rate at which the waveform fluctuates above and below baseline and is expressed in Hertz (Hz). Change in the frequency of the EMG represents changes in the conduction velocity of the motor unit action potentials. Thus, a decreased EMG frequency has been associated with slower action potentials as a result of muscle fatigue. However, muscle temperature may be inversely related to the frequency of the EMG, offsetting the fatigue-induced decreases in EMG frequency[2]. To ensure reliable data, previous studies have suggested that the EMG data should be normalized as a percent of the EMG center frequency at beginning of exercise[3].

Mean Power Frequency at the fatigue threshold (MPF_{FT}) is a muscular fatigue threshold that assesses the fatigue-induced decreases in the frequency content of the EMG signal as a function of power output over time to determine the onset of muscular fatigue[4]. MPF_{FT} is determined using the frequency of EMG current through electrodes and a cycle ergometer test. Once the test is complete, a regression-based algorithm is applied that averages the highest power output (in a non-significant slope coefficient greater than 0.05) with the lowest power output (in a significant negative slope coefficient less than 0.05)[5]. Previous studies have shown that a decrease in the frequency of EMG is proportional to muscular fatigue[6].

Another well-established fatigue threshold technique is the use of the D-Max regression algorithm. The D-Max has been widely used in metabolic parameters of fatigue, such as blood lactate levels to determine the anaerobic threshold. Lactate measurements are obtained through an incremental intensity exercise that continues until the participant reaches fatigue. Once the lactate levels have been gathered, they are placed on a scatter plot with the lowest and highest lactate levels connected with a straight line. Using a third-order polynomial as a line of best fit, the maximum distance between the straight and curved line will indicate the lactate threshold. Through previous investigations the D-max method has been proven to be a valid method in determining lactate threshold in response to an incremental cycle ergometer test[7]. No studies have used the D-Max method applied to the frequency content of the EMG signal to determine the onset of fatigue, which could be useful as a non-invasive technique of calculating muscular fatigue without the need of drawing blood samples. Thus, the purpose of the present study was to determine if the D-max regression-based algorithm provides an accurate method of determining fatigue using the frequency content of the EMG signal. Based on the findings of previous investigations we hypothesized that there will not be significant difference between the MPF_{FT} and D-max methods indicating the D-Max method using the frequency content of the EMG signal will be a better non-invasive alternative for the assessment of NMF[7-8].

Methods

Participants

Twenty-two (17 men, 5 women; mean ± SD; age=21.1 ± 2.8 years; body weight= 78.0 ± 12.7 kg; height= 177.4 + 9.6 cm) volunteered to participate in the investigation. All participants participated in regular physical activity. The study was approved by the University Institutional Review Board for Human Participants. Before testing, all participants completed a health history questionnaire and signed an informed consent document.

Instrumentation and Procedures

Maximal Cycle Ergometer Protocol

Each participant performed an incremental test to exhaustion on a Calibrated Lode (Corival V3, Groningen, the Netherlands) electronically braked cycle ergometer at a pedal cadence of 70 revŸmin^{-1}. Seat height was adjusted so that participants could perform near full leg extension while cycling. Heart rate was monitored using a Polar Heart Rate Watch system (Polar Electro Inc., Lake Success, NY). Borg's rating of perceived exertion (RPE 6-20) scale was explained to the participant and recorded for each stage of the test. The participants began the test pedaling at 50 W, and the power output was increased by 25 W after each 2 minute stage until voluntary exhaustion. The test was terminated if the participant met at least two of the following three criteria[9]: a) 90% of age-predicted heart rate (220-age), b) RPE of 18 or higher, and c) an inability to maintain the pedal cadence of 70 revŸmin^{-1}. After the test was finished the participants were encouraged to cool-down.

EMG Measurements

A bipolar surface EMG electrode (circular 4mm diameter, silver/silver chloride, Biopac Systems, Inc., Santa Barbara CA) arrangement was placed on the Vastus Lateralis of both legs according to recommendations from the SENIAM Project[10]. A reference line was drawn one third of the distance from the anterior superior iliac crest to the lateral border of patella[10]. The electrodes were placed 4 to 5 cm lateral from the reference line along a 20° angle[6-7,10]. The pennation angle was measured using a goniometer (Smith and Nephew Rolyan, Inc., Menomonee Falls, WI) to approximate the placement of the electrodes on the VL[11]. A reference electrode was placed over the tibial tuberosity on both legs. The measurements for the electrode placement were made using a standard measuring tape (Gulik Tape, II, Moberly, Missouri). Prior to placing the electrodes, the skin at each electrode site was shaved, abraded, and cleaned with an alcohol wipe. Interelectrode impedance was less than 2000 Ω. The EMG signal was amplified (gain: x1000) using differential amplifiers (EMG 100, Biopac Systems, Inc., Santa Barbara, CA, bandwidth= 10-500 Hz).

Signal Processing

The raw EMG signals from the VL were digitized at 1000 Hz and stored in a personal computer for subsequent analysis (Inspiron 1 520, Dell, Inc., Round Rock, TX). The signal processing was performed using a custom program written with LabVIEW programming software (version 7.1, National Instruments, Austin, TX). The EMG signals were bandpass filtered (fourth-order Butterworth) at 10-500 Hz[12].

Determination of MPF_{FT}

The MPF_{FT} was determined by averaging the highest power output that resulted in a non-significant ($p>0.05$; two-tailed t-test) slope coefficient for the EMG MPF vs. time relationship, with the lowest power output that resulted in a significant ($p<0.05$) negative slope coefficient (Figure 1). The MPF_{FT} was assessed for the dominant and nondominant legs using the same procedures.

Determination of the D-Max

A new method proposed to assess a fatigue threshold was the D-max method, which utilized an algorithm proposed by Cheng et al.[13] for assessing lactate thresholds and ventilatory thresholds[13]. A third-order curvilinear regression was fit to EMG frequency versus the power output relationship, and a straight line was drawn from the first and last data point of the curve. The point that yields the maximal perpendicular distance (D-max) from the straight line to the third-order curvilinear regression line was determined to be the D-Max fatigue threshold (Figure 2). The time to the nearest second of the D-max was then used to calculate the power output (W) for the fatigue thresholds (Figure 3).

Statistical analyses

Mean, standard deviation (SD), and range values were calculated for the power outputs determined by the MPFFT and D-max methods using the participant's' dominant leg. The relationships for EMG frequency and power output for each participant were examined using linear regression (SPSS software program, Chicago, IL). A paired dependent t-test was used to determine if there were significant mean differences in power outputs between the MPFFT and the D-max methods. A zero-order correlation was used to determine the relationships between the power outputs of the MPFFT and the D-max. An alpha level of $p \leq 0.05$ was considered significant for all statistical analyses.

Results

Table 1 displays mean, SD and range values for the physical characteristics of the participants. Table 2 provides the MPF_{FT} and D-max values that were determined for each participant based on the EMG frequency (Hz) of their dominant leg. The results of the dependent t-test indicated that there were not significant mean differences ($p>0.05$) between the MPF_{FT} and D-max values ($p=0.29$). The zero-order correlation for the power outputs determined by the MPF_{FT} and D-max methods showed that the two methods were moderately correlated ($r = 0.69$).

Table 1. Physical characteristics and mean, SD, and range values for fatigue thresholds (n=22).

Variable	Mean ± SD (range)
Age (years)	21.1 + 2.8 (19-33)
Body Weight (kg)	78.0 + 12.7 (52.2-108.4)
Height (cm)	177.4 + 9.6 (162.6-193.0)
MPFFT* (W)	161.9 + 44.9 (112.5-287.5)
D-max** (W)	168.9 + 36.6 (102.1-229.1)

*MPF_{FT}= EMG mean power frequency at the fatigue threshold.
**D-max = The point that yields the maximal perpendicular distance from the straight line to the third-order curvilinear regression line.

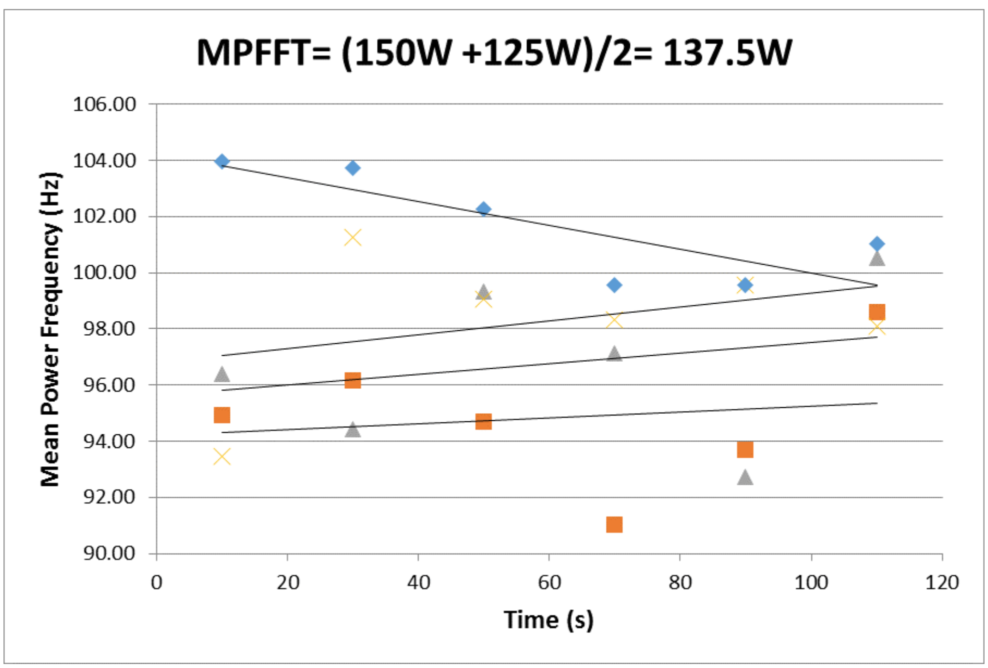

Figure 1. Example of method used for estimating the mean power frequency at the fatigue threshold (MPF_{FT}). The MPF_{FT} in the current example (137.5 W) was determined by averaging the highest power output (125 W) that resulted in non-significant ($p>0.05$) slope coefficient for the EMG frequency vs. time relationship, with the lowest power output (150 W) that resulted in a significant ($p\leq0.05$) positive slope coefficient. Slope coefficient significantly greater than zero at $p\leq0.05$.

Table 2. Individual, mean, and SD values for fatigue thresholds (n=22).

Participant	MPF_{FT}* (W)	D-max** (W)
1 (man)	187.5	212.474
2 (man)	122.5	149.984
3 (man)	187.5	189.561
4 (woman)	112.5	102.075
5 (man)	162.5	167.6895
6 (man)	137.5	181.229
7 (man)	162.5	219.7645
8 (woman)	137.5	167.6895
9 (man)	187.5	183.312
10 (man)	237.5	207.2665
11 (man)	137.5	228.0965
12 (man)	212.5	206.225
13 (woman)	162.5	159.3575
14 (man)	112.5	134.3615
15 (woman)	162.5	131.237
16 (man)	162.5	204.142
17(man)	287.5	229.138
18 (man)	162.5	168.731
19 (man)	237.5	227.055
20 (woman)	187.5	172.897
21 (man)	187.5	166.0231
22 (man)	237.5	245.802
Mean ± SD	161.9 ± 44.9	168.9 ± 36.6

*MPF_{FT}= EMG mean power frequency at the fatigue threshold.
**D-max = The point that yields the maximal perpendicular distance from the straight line to the third-order curvilinear regression line.

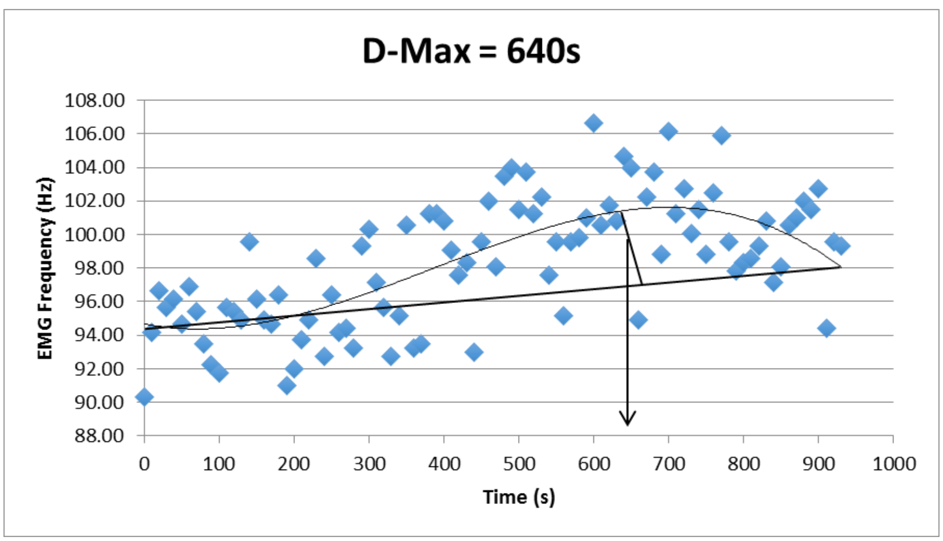

Figure 2. Example of D-max method used to determine the time to fatigue, to the nearest second, for the linear regression equation in Figure 3. The maximal perpendicular distance from the straight line to the third-order curvilinear regression line was determined to be the D-max. The independent variable, time (640s in the current example), was used to calculate the power output (W) for the fatigue thresholds with a linear regression equation (Figure 3).

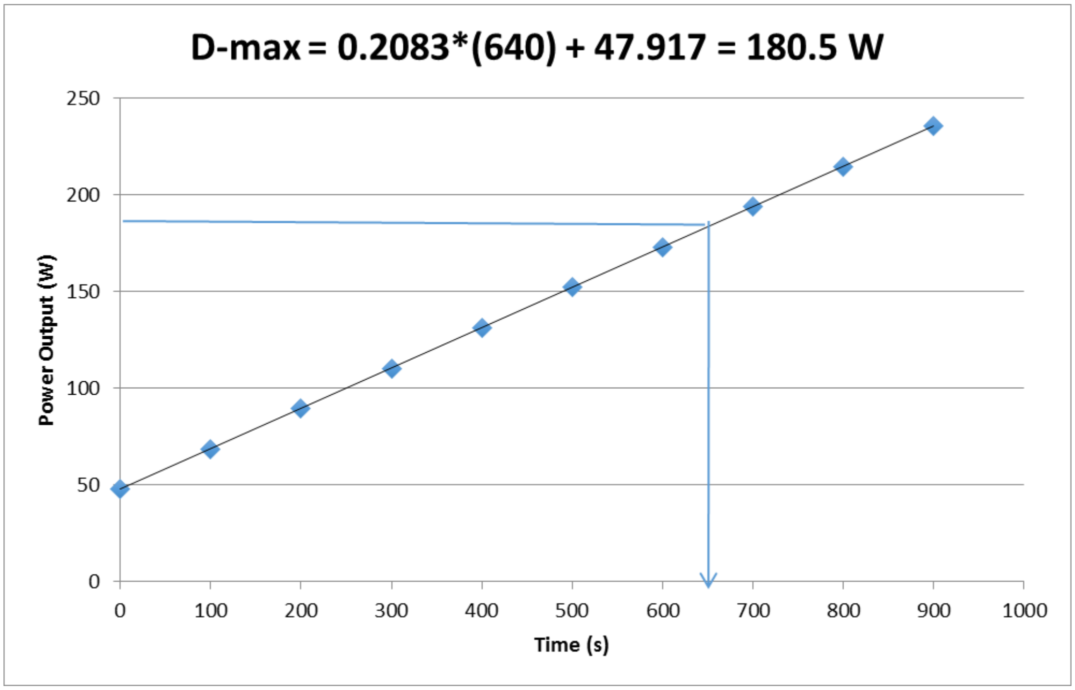

Figure 3. Example of method used to find the power output for the D-max. To calculate D-max thresholds a linear regression equation was used derived from the time and power output relationship as follows: D-max Power Output (W) = 0.2083*s + 47.917. In the current example W = 0.2083*(640s) + 47.917 = **180.5 W**.

Discussion

The purpose of this study was to determine whether there were significant differences between the MPF_{FT} and D-max methods in determining neuromuscular fatigue. MPF_{FT} is a known method to estimate the development of NMF, but using the D-max regression based algorithm associated with EMG frequency has been untested. Our hypothesis was that the two methods were not significantly different and thus used interchangeably. The present investigation found that the two regression-based algorithms did not produce significant mean differences ($p>0.05$, Tables 1 and 2). Using a zero order correlation, it was determined that the mean power output values for the MPF_{FT} (161.87 $\pm$ 44.85) and D-max methods (168.92 $\pm$ 36.62) were fairly correlated ($r=0.69$). These findings were in agreement with our hypothesis that the two algorithms would produce similar results.

Previous studies have shown that EMG frequency and amplitude are accurate techniques to predict the development of NMF[4]. In the past, PWC_{FT} has been used in determining the neuromuscular fatigue threshold delimiting the boundaries between moderate and heavy exercise domains while MPF_{FT} marks the boundaries between heavy and severe exercise intensity domains[4].

Previous studies have examined the effects of temperature on EMG frequency based fatigue thresholds[2]. Temperature was found to cause an increase in frequency content of the EMG signal offsetting the fatigue induced decline in frequency[2,4,9]. It is possible that by examining the EMG frequency responses of the overall test by using the D-Max method rather than individual stages using the MPF_{FT} methodology may be a better approach to ameliorate the effect of muscle temperature when determining the development of neuromuscular fatigue. To our knowledge no previous investigations have compared the use of MPF_{FT} and D-max methods for assessing neuromuscular fatigue thresholds. The implications of this study showed that D-max would be a reliable, comprehensive, and time-efficient method to assess NMF.

One of the limitations of the study was that only 22 participants were assessed. If more participants had been used there would have been less error and our statistical values would have been more accurate. Choosing the participants at random allowed for a diverse and representative sample, but also could have caused error since body composition, fitness level, sex and testing experience were not taken into account.

Based on the results of the present investigation it is recommended that future studies consider using the D-max method to assess NMF. Examining the entire test eliminates the potential for error found in the analysis of individual stages of the MPF_{FT} due to noise or a significant value that is not actually due to fatigue. As seen in Figures 2 and 3, the D-max predicts the time and frequency that NMF develops in a very accurate and mathematically sound technique. Furthermore, the D-max method is easier to use and only requires the ability to construct a graph with a third order polynomial regression curve using Excel program.

Conclusions

The present investigation found that there was no significant difference between the MPF_{FT} and D-max methods of calculating NMF. The findings of this study show that the D-max is an accurate regression based algorithm for assessing NMF. These findings are relevant for future studies because the D-max includes the entire cycle ergometry test EMG data providing an overall analysis and comprehensive assessment with less calculation than the MPF_{FT} method. Studies should consider using the D-max method as a means of calculating NMF in place of the MPF_{FT} method.

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