THE Dmax Method Is a Valid Procedure to Estimate Physical Working Capacity at Fatigue Threshold

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ABSTRACT: Introduction: The purpose of this study was to determine the validity of the maximal distance—electromyography (Dmax-EMG) method for estimating physical working capacity at fatigue threshold (PWCFT).

Methods: Twenty-one men and women (age 22.9 ± 3.0 years) volunteered to perform 12 sessions of high-intensity interval training (HIIT) over 4 weeks. Before and after HIIT training, a graded exercise test (GXT) was used to estimate PWCFT using the Dmax method and the original (ORG) method.

Results: There was a significant increase in PWCFT for both ORG (+10.8%) and Dmax (+12.1%) methods, but no significant difference in the change values between methods. Further, Bland–Altman analyses resulted in non-significant biases (ORG-Dmax) between methods at pre-HIIT (-6.4 ± 32.5 W; P > 0.05) and post-HIIT (-4.2 ± 33.1 W; P > 0.05).

Conclusion: The Dmax method is sensitive to training and is a valid method for estimating PWCFT in young men and women.

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In 1982, deVries et al.1 developed a test using electromyographic (EMG) fatigue curves from supramaximal, discontinuous work rates during cycle ergometry to determine power output at fatigue threshold (FT). This assessment is known as EMG at fatigue threshold (EMGFT) and has a strong relationship (r = 0.90) with anaerobic threshold (AT), as determined by gas-exchange parameters.2 Although deVries et al.3 concluded that FT evaluation with EMG values may provide an attractive alternative to existing methods, the supramaximal workloads used to determine EMGFT may not be appropriate for all populations (elderly, frail, etc.). Thereafter, deVries et al.3 developed a test that utilized discontinuous, submaximal incremental workloads and EMG fatigue curves to identify the power output corresponding to the onset of fatigue, which they termed physical working capacity at FT (PWCFT). More specifically, the PWCFT represents the highest power output that results in a non-significant increase in the electrical activity of the thigh muscles over time, and this protocol was subsequently found to produce very reliable results [intraclass correlation coefficient (ICC) = 0.976] that are sensitive to exercise training adaptations in elderly individuals.3,4

The submaximal PWCFT protocol involves an incremental series of 2-minute work bouts with rest intervals that allow participant heart rate values to return to within 10 beats/min of pre-exercise levels. Although the discontinuous PWCFT assessment has demonstrated strong reliability, validity, and sensitivity, the test requires a significant time commitment (1.5–2.0 hours). Thus, deVries et al.5 developed a continuous PWCFT test (the original method, or ORG) that examined consecutive 2-minute EMG fatigue curves and compared it to the discontinuous, incremental protocol in young men and women. The results show that the PWCFT values between the discontinuous and continuous protocols were not significantly different (P > 0.05), and had a strong relationship (r = 0.856). Because the time required to complete the continuous protocol was much less (~30 minutes), the authors concluded that this approach may be preferable to the discontinuous PWCFT test. Since modifying the PWCFT test, the ORG PWCFT assessment has demonstrated strong reliability (ICC = 0.94–0.976), validity,5 and sensitivity to changes in fitness level and/or nutritional interventions6–11 in young men and women.

Previous studies have described cases where no significant increase in EMG activity occurred over time, or where multiple significant (“false positive”) slopes were recorded during the incremental work bouts, making it difficult to identify the PWCFT in an objective manner.5,11,12 Thus, a potential limitation of the ORG method when determining PWCFT is unusable data in approximately 10% of subjects.8,11,12 Interestingly, common methods used to detect AT (both lactate and ventilatory) have also demonstrated similar

Abbreviations: ANOVA, analysis of variance; CE, constant error; Dmax, maximal perpendicular distance; EMG, electromyography; EMGFT, electromyography at fatigue threshold; FT, fatigue threshold; GXT, graded exercise test; HIIT, high-intensity interval training; ICC, intraclass correlation coefficient; LOA, limits of agreement; MD, minimal difference; ORG, original method; PWCFT, peak power; PWCFT, physical working capacity at fatigue threshold; rms, root mean square; SEC, standard error of the estimate; SEM, standard error of the measurement; TE, total error; T返, time of onset of fatigue; VT, ventilatory threshold

Key words: cycle ergometry; electromyography; neuromuscular fatigue; reproducibility; sensitivity; validity

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limitations (no breakpoint detected) because of the unreliable behavior of the physiological variables.\textsuperscript{13} Cheng et al.\textsuperscript{15} proposed another mathematical method, called Dmax, to identify fatigue thresholds. In principle, the Dmax method examines the linear regression line between physiological variables (lactate, ventilatory, EMG) measured at the start and end of an incremental exercise test, as well as a third-order polynomial regression line that represents the physiological response during the test. The point at which the maximal distance (Dmax) is measured perpendicularly from the linear regression line to the polynomial curve is defined as the fatigue threshold. The Dmax method has been shown to be reliable (ICC = 0.77–0.93) and valid when estimating lactate and ventilatory thresholds (VTs) during incremental cycle ergometry in men.\textsuperscript{13,14}

Bergstrom and colleagues\textsuperscript{15} reported use of the Dmax method in young men and women to determine the power output at the onset of neuromuscular fatigue (Dmax-EMG) and suggested that it demarcates the moderate and heavy exercise intensity domains during an incremental cycle ergometer test. Furthermore, they reported that the oxygen consumption rate at VT (2.38 ± 0.63 L/min) was not significantly different than the oxygen consumption rate at Dmax-EMG (2.21 ± 0.48 L/min) and that the 2 thresholds had a strong relationship ($r = 0.83$).

Recently, Miramonti et al.\textsuperscript{6} used the Dmax-EMG method to estimate power output at the onset of neuromuscular fatigue, demonstrating its reliability (ICC = 0.95) and sensitivity to high-intensity interval training (HIIT). They termed the calculated threshold PWC\textsubscript{FT}; however, this classification was premature, as the Dmax-EMG method has yet to be validated against the ORG PWC\textsubscript{FT} method.\textsuperscript{4,5} Therefore, the purpose of this study was to evaluate the validity of the Dmax-EMG method versus the ORG method for estimating and tracking changes in PWC\textsubscript{FT} with HIIT training.

METHODS

Subjects. Using the Excel random number function, 24 of 40 of participants from the Miramonti et al.\textsuperscript{6} study were selected for further methodological analysis; however, 3 subjects were dropped due to inability to determine PWC\textsubscript{FT} using the ORG method. Therefore, 21 subjects (11 men and 10 women; age 22.9 ± 3.0 years, height 172.5 ± 10.3 cm, body mass 72.3 ± 13.3 kg) were used in the final analysis. The study protocol, benefits, and risks were explained before signing the informed consent. Health history, activity levels, and previous nutritional supplementation of participants were evaluated using a physical activity readiness questionnaire (PAR-Q) and a health and activity history questionnaire. The study was approved by the institutional review board of the university. All participants signed an informed consent form before any data collection.

Protocol. On the first testing day (pretraining), anthropometric measures of age (years), height (cm), and body mass (kg) were collected from participants. To calculate PWC\textsubscript{FT}, each participant performed a graded exercise test (GXT) on an electrically braked cycle ergometer (Excalibur Sport, Groningen, The Netherlands) until volitional fatigue. The peak wattage achieved (P\textsubscript{PEAK}) was used to establish individual training intensity. Subjects then completed 12 HIIT sessions before post-testing. Sessions were scheduled 3 times per week for 4 weeks on nonconsecutive days and were performed on an electrically braked cycle ergometer. After the HIIT, subjects returned to the laboratory for post-testing and repeated the same procedures as during pre-training testing.

EMG Measurements. A bipolar (4.6 cm center-to-center) silver–silver chloride surface electrode (Quinton Quick-Prep) arrangement was placed over the vastus lateralis (VL) muscle on the right thigh, and a reference electrode was placed over the lateral epicondyle. The EMG electrodes were placed on the VL, precisely two-thirds distance from the anterior superior iliac spine to the lateral patella, based on recommendations from the Surface Electromyography for Non-invasive Assessment of Muscles (SENIAM) project for EMG electrode placement.\textsuperscript{19} Before electrode placement, the skin at each site was shaved and cleaned with alcohol. Inter electrode impedance was kept below 5,000 $\Omega$ with careful abrasion of the skin beneath the electrodes. The raw EMG signal was sampled at 1 kHz, differentially amplified (EMG 100c, bandwidth 10–500 Hz, gain $\times$2,000; MP150, Biopac Systems, Inc., Santa Barbara, California), and digitally bandpass filtered (zero-phase shift fourth-order Butterworth filter) at 10–500 Hz. The EMG signals were stored on a personal computer (Latitude E6530; Dell, Inc., Round Rock, Texas) and expressed as root-mean-square (rms) amplitude values ($\mu$Vrms).

ORG Method for Estimating PWC\textsubscript{FT}. The PWC\textsubscript{FT} values using the ORG method were estimated during the GXT using procedures adapted from deVries et al.\textsuperscript{3,5} During each 2-minute stage, 6 10-second EMG samples were recorded from the VL. The average EMG amplitude values (rms) were calculated for each 10-second epoch and were then plotted across time for each power output. The PWC\textsubscript{FT} was defined as the average of the highest power output that resulted in a non-significant ($P > 0.05$;
1-tailed t-test) slope coefficient for the EMG amplitude-vs.-time relationship and the lowest power output that resulted in a significant ($P < 0.05$) positive slope coefficient (Fig. 1).

**Dmax Method for Estimating PWC<sub>FT</sub>.** PWC<sub>FT</sub> was calculated using the Dmax method, as described previously.6 The average rms values were calculated for each 10-second epoch during the GXT. To reduce variability, any 3 consecutive rms value points were averaged and then plotted against the midpoint of each 30-second window17 (Fig. 2). Participant warm-up values were excluded from analysis, whereas the remaining data points were used to generate a third-order polynomial regression, demonstrating an increasing EMG amplitude in the time domain during the GXT.

The point of fatigue ($T_F$) (Fig. 3) was the point on the third-order polynomial regression that was the maximum perpendicular distance from that linear regression of the starting and ending points of the GXT. $T_F$ was used to identify the power output that represented the PWC<sub>FT</sub>.

**High-Intensity Interval Training.** The HIIT training protocol is illustrated in Figure 4. Briefly, training sessions commenced with a 5-minute warm-up at a self-selected power output followed by 5 2-minute work bouts, then 1 minute of rest. Training intensity of each HIIT session ranged from submaximal (85%) to supramaximal (120%) P<sub>PEAK</sub> level.6 If a participant was unable to complete an assigned work bout, the amount of time completed was recorded, and the 1-minute rest period began thereafter. Participants performed HIIT sessions 3 times per week for 4 weeks on non-consecutive days on an electronically braked cycle ergometer (Corival, Lode, Groningen, The Netherlands). All training sessions took place under the supervision of a certified fitness specialist.

**Statistical Analysis.** A 2-way measures analysis of variance (ANOVA) was used to identify method × time interaction for PWC<sub>FT</sub>. If significant interaction occurred, Bonferroni-adjusted independent t-tests were run on pre- and post-PWC<sub>FT</sub> values between groups. If a significant main effect occurred, paired samples t-tests were run to determine the pre- to post-change scores for each method.

The validation analysis of the Dmax method used in this study at pre- and post-HIIT were based on the evaluation of the criterion PWC<sub>FT</sub> (ORG) vs. the Dmax-estimated PWC<sub>FT</sub> via calculation of the constant error (CE = mean difference for ORG PWC<sub>FT</sub> – Dmax PWC<sub>FT</sub>), Pearson product-moment correlation ($r$), standard error of estimate [SEE = SD<sub>y</sub>($1 - r^2$)], and total error [TE = $\Sigma$[(ORG<sub>PWC<sub>FT</sub></sub> – Dmax<sub>PWC<sub>FT</sub></sub>)<sup>2</sup>] / n]. In addition, the Bland–Altman approach20 was used to assess agreement between methods for pre- and post-estimates of PWC<sub>FT</sub>. Statistical significance was set at an alpha level of 0.05. Data were analyzed using SPSS, version 23.0 (SPSS, Inc., Chicago, Illinois).

**RESULTS**

The repeated-measures ANOVA revealed no significant method × time interaction ($P = 0.957$) and no main effect for method ($P = 0.235$), but a significant main effect of time was observed ($P <$
HIIT improved PWCFT from pre to post (Table 1) when determined by Dmax (pre: 164.3 ± 37.6 W; post: 186.9 ± 35.9 W; P < 0.001) and ORG (pre: 170.7 ± 56.9 W; post: 191.1 ± 57.1 W; P < 0.008).

Table 2 lists the results of the cross-validation analysis. The mean difference (CE) between the ORG and Dmax PWCFT at pre (–6.5 ± 32.5 W; P = 0.375) and post (–4.2 ± 33.1 W; P = 0.564) were not significantly different. Further, the validity coefficients for pre (r = 0.84) and post (r = 0.84) were considered very strong. The TE, which accounts for the errors associated with both the CE and SEE, was 32.3 W and 32.6 W for pre and post PWCFT values, respectively.

The Bland–Altman plot is displayed in Figure 5. The 95% limits of agreement (LOA) ranged from –58.49 to 71.34 W. The regression line shows that the Dmax method overestimated PWCFT at low power outputs and underestimated it at high power outputs compared with the ORG method, with a weak, negative correlation (r = −0.435; P = 0.049). However, all participants fell within ±1.96 standard deviations of the mean difference.

In the post analysis, the Bland–Altman plot showed LOA values ranging from −62.00 to 70.48 W. In addition, the regression line in Figure 6 shows the Dmax method overestimated PWCFT at low power outputs and underestimated it at high power outputs compared with the ORG method, with a moderate, negative correlation (r = −0.604; P = 0.004). Nonetheless, all participants fell within ±1.96 standard deviations of the mean difference.

**DISCUSSION**

Previous studies have shown high reliability (ICC = 0.85–0.975) and low Standard error of the measurement (SEM ± 6 to 11 W). When estimating PWCFT in men and women using the ORG method proposed by deVries et al.,

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**FIGURE 3.** Dmax method to determine T_F. The circles represent the 30-second averages of the original RMS values, whereas the solid black line represents the third-order polynomial regression of the data. The diamonds represent the first and last data points in the analysis, and the dashed line is the linear regression between those 2 points. The linear line connecting the linear regression and the third-order polynomial regression is the maximal perpendicular distance (Dmax). The dotted line that continues under the maximum perpendicular distance line shows the T_F from the third-order polynomial regression. RMS, root mean square \((\mu V_{rms})\).

**FIGURE 4.** Illustration of the HIIT protocol. Each bar represents the training intensity for every session, which ranged from 85% to 120% of peak power achieved during a graded exercise test. Each training session consisted of 5 2-minute bouts of work followed by 1 minute of rest.

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Miramonti et al. demonstrated very strong test–retest reliability (ICC = 0.949; SEM = 6.8 W) when estimating PWC_{FT} using the Dmax method. Although the ORG method has been reported to be very reliable, previous studies, including ours, have reported unsatisfactory data in approximately 10% of subjects, who were thus dropped from the study. For example, when using the ORG method, unsatisfactory data included tests in which there was no EMG evidence of muscular fatigue (significant slope coefficient), and therefore PWC_{FT} could not be determined. However, in our study, a PWC_{FT} was estimated in all of the participants using the Dmax method. Although both methods provide high reliability, the Dmax method may overcome the shortcomings of the ORG method when estimating PWC_{FT}.

These findings indicate that the work rates at PWC_{FT} estimated by the Dmax and ORG methods were not significantly different and had a strong correlation for pre-HIIT ($r = 0.84$) and post-HIIT ($r = 0.84$; Table 2). In addition, there was a significant increase in PWC_{FT} for ORG (+10.6%) and Dmax (+12.1%), but no significant difference in the change values between measures (Table 1). Furthermore, the SEE values for pre-training (31.6 W) and post-training (31.6 W) were similar. When the SEE values were expressed as a percentage of the mean of the ORG PWC_{FT} (%SEE), the values for pre and post were 19.9% and 17.0%, respectively. It has been suggested that SEE values ranging between 10% and 20% are typical of methods used to estimate maximal oxygen consumption and VT measures. The %SEE values observed for PWC_{FT} in our study were similar to cross-validation estimates of VT reported by Malek et al. (18%–20%).

Although the SEE provides important information regarding error associated with the regression between ORG and Dmax, the TE is the best criterion for determining the accuracy of the prediction, because it combines the errors associated with CE and SEE. Furthermore, it has been suggested that valid predictions will exhibit similar values for SEE and TE. In our study, the TE and %TE values for pre (32.3 W; 18.9%) and post (32.6 W; 17%) were very similar to SEE values (Table 2), which suggests the estimated PWC_{FT} from the Dmax method is valid when compared with the ORG method before and after HIIT. Bland–Altman plots (Figs. 5 and 6) revealed no systematic biases between ORG and Dmax for pre-training ($-6.5 \pm 32.4$ W; $P = 0.375$) and post-training ($-4.2 \pm 33.1$ W; $P = 0.564$). In addition, 100% of participants fell within ±1.96 standard deviations of the mean difference for pre and post, respectively.

In conclusion, our findings suggest that the Dmax method is sensitive to training and is a valid method to estimate PWC_{FT} in young men and women. Future studies are needed to validate the

| Table 1. Baseline values and change in PWC_{FT} after HIIT (mean ± SD) |
|-----------------------------|-------------|-------------|
| Method | Variable | Pre (W) | Post (W) |
| ORG | PWC_{FT} | 170.7 ± 56.9 | 191.1 ± 57.1* |
| Dmax | PWC_{FT} | 164.3 ± 37.6 | 186.9 ± 35.9* |

*Significant change ($P < 0.05$) from pre to post.

| Table 2. Validation of PWC_{FT} pre- and post-training |
|-----------------------------|-------------|-------------|
| Method | PWC_{FT} (W) (mean ± SD) | CE | $r$ | SEE (W) | SEE% | TE (W) | TE% |
| Dmax pre | 164.3 ± 37.6 | 6.4 | 0.84 | 31.6 | 18.5 | 32.3 | 18.9% |
| ORG pre | 170.7 ± 56.9 | -6.4 | 0.84 | 31.6 | 18.5 | 32.3 | 18.9% |
| Dmax post | 186.9 ± 35.9 | -4.2 | 0.84 | 31.6 | 16.5 | 32.6 | 17.0% |
| ORG post | 191.1 ± 57.1 | -4.2 | 0.84 | 31.6 | 16.5 | 32.6 | 17.0% |

SEE% calculated as SEE / mean of actual PWC_{FT}; TE% calculated as TE / mean of actual PWC_{FT}. |
Dmax method for estimating PWC_{FT} in other populations, such as youth and older men and women.

REFERENCES


