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VO₂ PLATEAU DETECTION IN CYCLE ERGOMETRY

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ABSTRACT

VO₂ PLATEAU DETECTION IN CYCLE ERGOMETRY. **Joseph P. Weir, Sara Koerner, Brent Mack, Jason Masek, David Vanderhoff and Bryan C. Heiderscheit.** *JEPonline*. 2004;7(2):55-62. Recently, the presence of a plateau in VO₂ at maximal work rates has been questioned. Currently, there is no consensus regarding the appropriate criteria for detecting a plateau, and criteria based on absolute changes in VO₂ (e.g. 150 ml/min) are problematic considering differences in workload increments and body size. In addition, the time interval over which to evaluate changes in VO₂ (breath-by-breath (BxB) vs. various time averages) is not established. To avoid these concerns, we applied signal-processing techniques common in biomechanics to examine the presence of the plateau. Twenty subjects (10 males and 10 females) performed two individualized incremental ramp protocols to exhaustion (pedal rev/min < 40) on an electrically braked cycle ergometer interfaced with a metabolic cart. The first test was for subject familiarization, while the results of the second test were analyzed. To create evenly spaced data points, each BxB VO₂ signal was interpolated (cubic spline), re-sampled at 60 Hz, normalized to the maximal VO₂ and then smoothed (Butterworth low pass filter, cutoff = 0.02 Hz). The first derivative (FD) signal was calculated (mean of means = 0.12 ± 0.01% max/s) and FD minima (FDM; criteria = 2 SD below mean FD) were identified. Of the 20 subjects, 12 had one FDM and 8 had two. All FDM were < 0.0 (mean ± SD = -0.82 ± 0.98 % max/s). Sixteen trials had FDM occur within the last 5 % of the ride (0.6 ± 1.2%), indicating changes in VO₂ indicative of a plateau (this was supported by visual examination in all cases). These were easily distinguished from the FDM not associated with plateaus because their positions were 41.5 ± 16.8% from the end of the ride (end = 100%). These results indicate that: 1) the plateau is evident in most subjects (16 of 20), and 2) the FDM criterion may be useful in objectively identifying the VO₂ plateau.

Key Words: exercise, interpolation, filters, plateau

INTRODUCTION

Maximal oxygen uptake (VO₂max) is traditionally defined as the maximal rate at which oxygen can be taken up and used by the body during exercise (1). VO₂max has been widely accepted as the best measure of functional capacity of the cardiovascular system and is regarded as a measurement of one's overall aerobic fitness (2). Indeed, determination of VO₂max has become a routine procedure in exercise physiology laboratories.

During an incremental exercise test, as power output increases there is a linear increase in oxygen uptake (VO₂). Current dogma suggests that there is a power output beyond which no further increase in power can raise VO₂max. At this point, defined as VO₂max, VO₂ will plateau or decrease slightly. It is typically argued that the limit of the central cardiovascular system to generate cardiac output is the primary determinant of VO₂max (1-6).

Recently however, Noakes (7-9) has questioned the validity of a VO₂max plateau and argues that there is a "muscle factor" that limits VO₂max. Specifically, Noakes (7-9) argues that there is no plateau in VO₂max and that studies typically cited as evidence of a plateau do not in fact demonstrate a plateau (1,4-6). Our review of literature indicates that there are surprisingly few studies demonstrating a clear plateau in VO₂max during typical VO₂max testing. Thus, the arguments of Noakes (7-9) appear to have some merit and warrant further examination.

Complicating the determination of a plateau in VO₂max is that no widely accepted criteria exist for defining when a plateau occurs (10). The basis for plateau detection is that the rate of increase in oxygen consumption with a given change in power must decrease, and in the case of a strict definition of a plateau, the VO₂ must not increase at all. Thus, all approaches must examine changes in the rate of VO₂ increase, i.e., the slope. In theory, a true plateau would be manifested with a slope of zero. In practice, a variety of criteria has been employed and can be divided into absolute and relative criteria. As an example, the classic paper of Taylor et al. (6) introduced the 150 mL/min criterion, i.e., an increase in work-rate that elicited a increase in VO₂ of ≤ 150 mL/min was considered evidence of a plateau. Absolute criteria, however, are protocol specific (due to differences in work-rate increments) and in the case of treadmill protocols, the expected change in VO₂ depends on body size. Relative criteria are based on a change in VO₂ slope relative to the pattern seen prior to the particular work-rate increment. This avoids the above-mentioned concerns with absolute criteria, but leaves one with a decision regarding how much change in slope defines a plateau. As an example, Myers et al (10) used a statistical criterion in which slope values were tested as to whether they were significantly different from zero. Breath-by-breath data from treadmill tests were smoothed using a variety of time and breath averages. Their results showed that the variability in oxygen uptake data "*was large enough to render any determination of a plateau meaningless*". However, the data smoothing approaches employed by Myers et al. (10) presents a variety of problems, not the least of which is that this approach leaves the frequency characteristics of the smoothed and non-smoothed data undefined. Indeed, it is quite possible that the large variability reported by Myers et al. (10) was simply due to inadequate attenuation of high frequency noise. In contrast, use of standard digital signal processing techniques such as interpolation and filtering may adequately smooth breath-by-breath oxygen uptake data so that a plateau, if present, will be revealed.

Therefore, the purpose of this study was to determine whether a plateau in VO₂ is identifiable during incremental exercise testing. To that end, subjects performed an incremental exercise test to exhaustion while breath-by-breath gas exchange data were collected. The data were then subjected to digital signal processing procedures for the purpose of identifying VO₂ plateaus.

METHODS

Subjects

Twenty healthy subjects (10 male and 10 female) were recruited from the student population at Des Moines University. The mean \pm SD for age, height, and mass of the subjects were 24.1 ± 1.3 yr, 178.3 ± 7.8 cm and 76.4 ± 15.5 kg, respectively. All subjects completed a health history form, and subjects with lower extremity injuries or cardiovascular disease were excluded from this study. In addition, all subjects signed a written informed consent before volunteering for the study. The consent and all procedures were approved by the Institutional Review Board of Des Moines University-Osteopathic Medical Center.

Exercise Testing

Subjects visited the laboratory on two occasions. All testing was performed with the subjects wearing t-shirt and shorts. During the first visit, subject's performed an incremental exercise test to exhaustion on an electrically braked cycle ergometer (Examiner Clinical Ergometer, Lode BV, Netherlands), which was interfaced with the laboratory's metabolic cart (see below). The purpose of this first test was to familiarize the subjects to the testing and to allow optimization of the test protocol on the second visit. The choice of power output increment was based on each subject's estimated VO₂max. VO₂max was estimated using the following regression equation: $\text{VO}_2\text{max (mL/kg/min)} = 1.92 \times (\text{sweat days}) + 23.76$, where "sweat days" referred to the self reported number of days per week that the subject exercises at a level sufficient to cause sweating (11). From this equation, the subject's maximal power output was estimated using a conversion constant of 10 ml O₂/min/Watt (12).

A slope for the cycle ergometer power increase (Watts/min) was then calculated so that the estimated maximal power output would be achieved in 10 minutes of exercise (13). The slope was programmed into the cycle ergometer using a continuous ramp protocol. Subjects were seated on the cycle ergometer and seat height and handlebar positions were adjusted to the subject's specifications. The subjects were interfaced to the metabolic cart (Max1, PhysioDyne, Instrument Corp, Quogue, NY) via a two-way non-breathing valve (2700 series, Hons Rudolf, Kansas City, MO). Prior to each test, the metabolic cart was calibrated according to the procedures of the manufacturer. Resting gas exchange data were measured for three minutes before the ramp protocol (start = 0 Watts) was initiated. The subjects were instructed to maintain a pedal rate of 70 rev/min. Termination of the test occurred when the subjects were unable to maintain a pedaling cadence of 40 rev/min. Heart rate was recorded continuously using a heart rate monitor (Polar Heartminder, Port Washington, NY) interfaced with the metabolic cart. Blood pressure (auscultation) and rating of perceived exertion were recorded every three minutes.

At least one week later, the subjects visited the laboratory a second time. All analyses described below were performed on the results from this second laboratory visit. During this visit, subjects performed another maximal oxygen consumption test with the ramp slope modified based on the data obtained from the initial test. Specifically, the ramp slope was adjusted so that the peak power output from the first test would be achieved in 10 minutes. In addition, the subjects were made aware of the peak power achieved during the first test and were encouraged to exceed this value if possible. All other procedures were the same as those described above. Following completion of the incremental test, the subjects were given at least 30 minutes of seated rest. Following the rest period, the subjects performed a constant workload exercise bout at a power output equal to 5% greater than the power that elicited VO₂ peak on the incremental test. A 30 second ramp was allowed to reach this constant power output, and subjects pedaled until they could not maintain a pedaling cadence of 40 rev/min.

Data Analysis

The breath-by-breath gas exchange data and power output were converted to ASCII files and subsequently analyzed using a custom program written with LabVIEW programming software (National Instruments, Austin TX). The processing of the VO₂ data involved three steps: normalization, interpolation, and smoothing (low pass filtering). Normalization involved determining the slope of the VO₂ vs. time relationship over the middle 50% of the ride using linear regression. This slope was then extrapolated to the time at test termination. All

VO₂ values were then normalized to this value. Similarly, the power data were normalized so that all values were plotted as a percentage of the peak power output. The normalization allowed VO₂ and power to be visualized together so that plateau in VO₂ would be more easily identified, however it had no effect on the quantitative plateau detection described below.

Since the VO₂ data were reported on a breath-by-breath basis with the time code for each breath corresponding to the particular time when the breath occurred, the time intervals between adjacent data points were not equal. In order to create evenly spaced data points, the normalized VO₂ values were fit with a cubic spline interpolation function, which was then re-sampled at a rate of 60Hz. This normalized and interpolated signal was smoothed using a zero lag low-pass Butterworth digital filter with a cut-off frequency of 0.02 Hz. This cutoff frequency was chosen because pilot work in our laboratory indicated the dominant low frequency component of the VO₂ signal was confined to frequencies below this value (see Figure 1), with high frequency breath-by-breath fluctuations located above this cutoff.

The process of plateau detection involved calculating the first derivative of the smoothed breath-by-breath VO₂ signal. The first derivative signal was evaluated for minima (first derivative minima; FDM) defined as values that were at least two standard deviations below the mean of the first derivative signal. The FDM indicate changes in the slope of the smoothed breath-by-breath VO₂ signal. If an FDM occurred in the last 10% of the ride, a plateau was identified. Thus, our criterion for defining a plateau was the presence of an FDM in the last 10% of the ride.

Statistical Analyses

To determine if the number of trials that exhibited a plateau were greater than those not exhibiting a plateau, the data were analyzed using the binomial test (14). In addition, to verify maximal effort, the peak VO₂ data from the incremental test were compared to the peak VO₂ from the +5% constant power ride using a paired t-test. For both tests, α was set at 0.05.

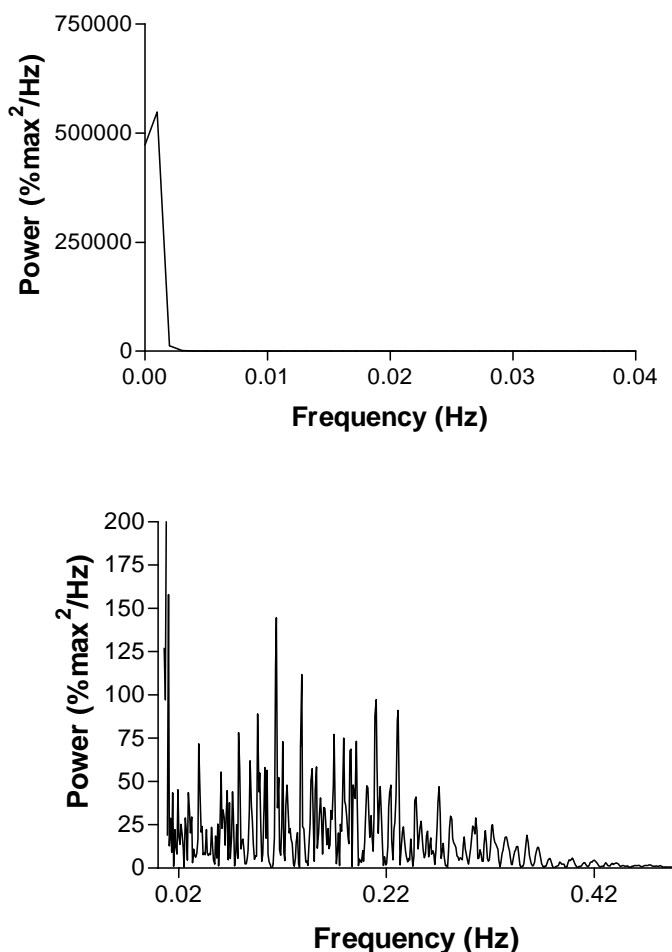


Figure 1. Top: Power spectrum of an interpolated and normalized VO₂ signal from a representative subject. Note the dominant power located at very low frequencies. Bottom: Power spectrum of same data as in the top, except that only frequencies above 0.02 Hz are shown. While the power in the high frequencies is small relative to the low frequency component that reflects the VO₂ trend (top), filtering of these frequencies results in a markedly smoother signal that aids in the identification of a VO₂ plateau.

RESULTS

Of the 20 subjects, 12 had one FDM and eight subjects demonstrated two FDM. All FDM were less than 0.0 (mean = -0.82 ± 0.41 % max/s). Of the 20 subjects, 16 had FDM occur within the last 5% of the ride (mean = $0.6 \pm 1.2\%$), indicating changes in VO₂ reflective of a plateau (this was supported by visual examination in all cases), while four subjects did not exhibit a plateau with this criterion. The Binomial test showed that a significantly ($p = 0.012$) larger number of subjects demonstrated a VO₂ plateau than those not exhibiting a plateau. The 16 FDM associated with plateaus were easily distinguished from the FDM not associated with plateaus since the non-plateau FDM occurred early in the ride ($41.5 \pm 16.8\%$ from the end of the ride; end = 100%). In addition, the comparison between the peak VO₂ from the incremental tests (mean = 42.7 ± 7.2 ml/kg/min) and the +5% constant power ride (mean = 40.2 ± 6.7 ml/kg/min) was significant ($p = 0.014$), further indicating that the incremental test elicited a plateau since an exercise bout at a higher power did not result in an increased VO₂ above that achieved during the incremental test.

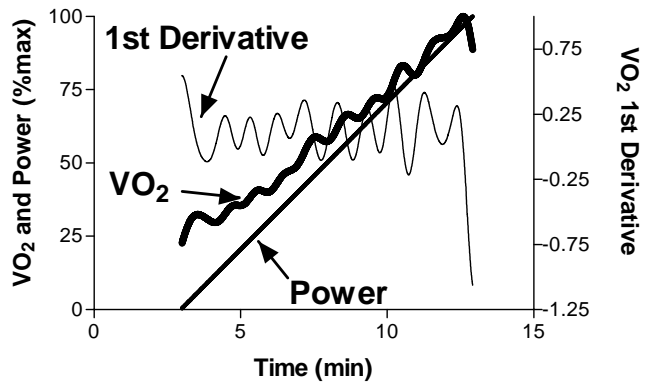
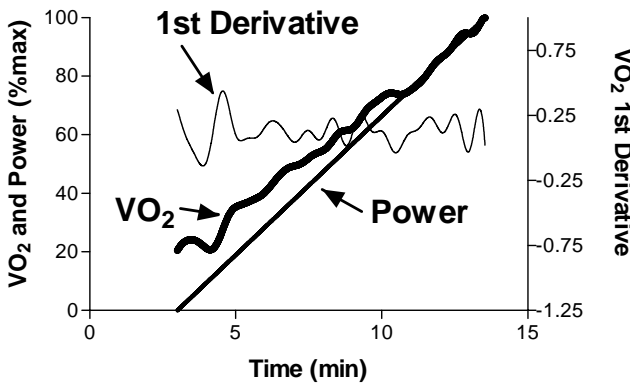
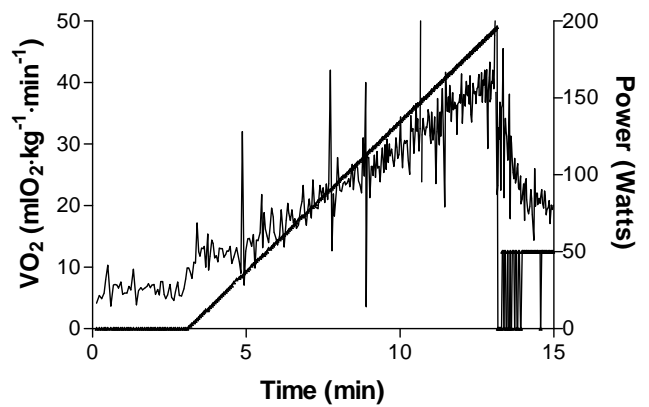
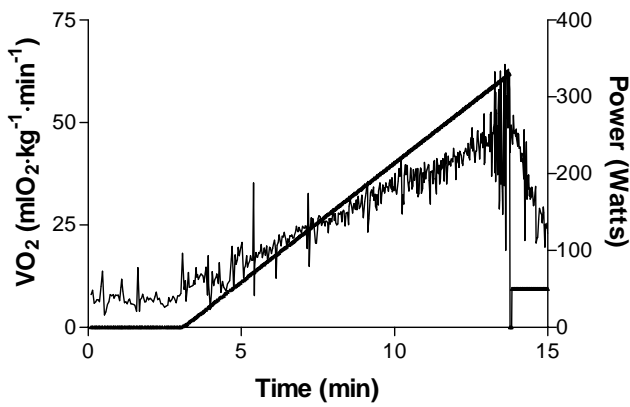


Figure 2. Top: VO₂ and power data for a subject who did not exhibit a plateau. Bottom: Smoothed VO₂, power, and 1st derivative of the VO₂ signal for the subject above who did not exhibit a plateau. Note the relatively continuous increase in VO₂ and the oscillatory nature of the 1st derivative.

Figure 3. Top: VO₂ and power data for a subject who did exhibit a plateau. Bottom: Smoothed VO₂, power, and 1st derivative of the VO₂ signal for the subject above who did exhibit a plateau. Note the change in VO₂ near maximal exercise and the associated dramatic drop in the 1st derivative.

To illustrate the effects of the signal processing, the data from a subject not exhibiting a plateau are shown in the top of Figure 2, while the smoothed data are shown in the bottom. Note that the breath-by-breath variability makes it difficult to determine whether a plateau is present, while the smoothed data provide a clear indication that a plateau was not achieved. In contrast, Figure 3 shows data from a subject who had an FDM that met the plateau criteria. The variability in the raw breath-by-breath data obscures the plateau that is evident when smoothed as seen in the top of Figure 3. These results indicate that: a) the plateau is evident in most trials (16 of 20), and b) the FDM criterion may be useful in objectively identifying the VO₂ plateau.

DISCUSSION

The primary purpose of this study was to determine if a plateau could be identified from breath-by-breath data derived from maximal exercise testing using a continuous protocol. Recently there has been debate over the concept of VO₂max and the VO₂ plateau (7), which has led to a re-examination of the original work done by Hill and Lupton (1). Specifically, Noakes (7) has argued that during incremental exercise to exhaustion, there is no plateau in VO₂ at maximal work rates. Our data, and recently those of Astorino et al. (15) do provide evidence of a VO₂ plateau. In this study, a plateau was evident in 16 of the 20 subjects (based on the FDM criteria). In addition, an exercise bout at a power 5% higher than that achieved during the incremental test failed to elicit a higher VO₂. Similarly, Astorino et al. (15) found that when shorter sampling intervals (11 breath and 15 s averages) were used, there was 100% incidence of a plateau in VO₂ at VO₂max with an increase in O₂ demand.

Central to the validity of these observations is whether the criteria for plateau detection are appropriate. Presently, there is no consensus regarding the appropriate criteria for detecting a plateau in maximal exercise testing. Most criteria are based on a minimal change in absolute VO₂. However, these criteria are problematic due to the effects of differences in work-rate increments and body size.

Howley et al. (2) have noted several examples of plateau criteria for early exercise physiology studies (see their Table 1). All are based on a change in VO₂ that is smaller than would be expected given the increase in workload. However, these criteria are limited to the particular protocol used in the study from which they were derived. In contrast, our approach can be adapted to any protocol, which is especially useful when using individualized protocols (13).

Additionally, the time interval over which to average VO₂ data (breath-by-breath vs. various time averages) has not been established. Howley et al. (2) recommended that the data be averaged over at least 60 s. to provide an accurate VO₂ max value. Specifically, they argued that short-averaging periods conspire with the variability in non-steady state VO₂ measures to overestimate maximal VO₂ if the highest time averaged value is taken as the VO₂ max. In contrast, Robergs (16) notes that since the increase in VO₂ deviates from linearity as one gets closer to maximal exercise, the use of long averaging intervals (≥ 60 s) artificially linearizes the data, and argues that the most sensitive approach to detecting a plateau would require use of “appropriately smoothed” breath-by-breath data. Furthermore, use of longer averaging periods would require subjects to exercise for extended periods of time at maximal and supra-maximal periods of time in order for a plateau to be detected (16).

We agree that use of long averaging periods can serve to mask the plateau phenomenon, and that plateau detection is facilitated by breath-by-breath data. Our approach however, differs from that of Astorino et al. (15) in two regards. First, rather than smoothing the data using a moving average, we specifically filtered high frequency components of the VO₂ curve. The cut-off frequency of 0.02 Hz used in this investigation was estimated using a combination of Winter’s (17) residual analysis technique and subjective evaluation. The underlying low frequency trend in the VO₂ signal was the primary frequency of interest. This frequency was estimated to be 0.0004 Hz (1/2400 s), assuming the observed VO₂ data to simulate one fourth of a sinusoidal

cycle. The cut-off frequency of 0.02 Hz was 50 times that of the estimated frequency of interest, thereby minimizing any effect to it. This approach has several advantages over moving averages: 1) the ideal number of breaths over which to average has not been established (the greater the number of data points that are included in the average, the greater the attenuation of higher frequencies); 2) the use of a moving average approach is not specific with respect to the frequency characteristics that are removed while the use of a digital filter allows for the low-pass filtering at a specific frequency cut-off, in this case 0.02 Hz; 3) the fact that the breaths vary with respect to both the magnitude of the VO₂ and the time interval between adjacent breaths complicates the choices regarding the time point to assign each averaged breath and the weighting used for calculating the relative contribution of each breath to the averaged breath. These concerns also apply to the approach employed by Myers et al. (10), in which a variety of time averages (60, 30, 20, 15, 10 and 5 seconds) and three breath-by-breath moving averages were evaluated.

Second, the criteria for plateau detection was based on the response of the first derivative (slope) as opposed to an absolute change in VO₂ of 150 mL/min (6) or 50 mL/min between adjusted data points (15). The use of absolute criteria such as 150 mL/min or 50 mL/min criteria presents challenges to broad application since differences in both body size and workload increments between protocols affect the expected change in VO₂ per unit of time. For example, in our study, we had three subjects whose average VO₂ slope was less than 150 mL/min across the incremental test. *A priori*, the 150 mL/min criterion is inappropriate for these subjects. Astorino et al. (15) used the 50 mL/min criteria when comparing adjacent data points using different averaging intervals. As the averaging intervals are varied, the workload increment between adjacent data points becomes different. Thus, the expected change in VO₂ between adjacent data points varies with the change in averaging interval. Collectively, the use of the FDM criterion avoids these concerns and lends itself to broad application.

CONCLUSIONS

Application of digital signal processing to breath-by-breath VO₂ data revealed that 16 of the 20 subjects in this study exhibited a VO₂ plateau while using the FDM criterion. Future research is needed to validate this response, in particular to data derived from different protocols and testing modes, such as the treadmill.

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