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PHASE TRANSITION DEFINES STEADY STATE BEYOND THRESHOLD

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ABSTRACT

PHASE TRANSITION DEFINES STEADY STATE BEYOND THRESHOLD. **Wyatt F, Autrey L, Fitzgerald Y, Colson S, and Heimda J**. **JEP**online. 2004;7(2):70-76. The purposes of this study were to: 1) determine physiological kinetics during steady work beyond thresholds, and 2) establish a paradigm identifying thresholds as phase transitions. Nineteen subjects (19) were tested. Measures included the expired gases (VO_2, VCO_2, RER), time to exhaustion (TE) and heart rate (HR). Subjects performed two tests on a cycle ergometer: 1) graded exercise test (GXT) and 2) performance exercise test (PXT) to volitional fatigue. The GXT established peak capacities and identified thresholds including ventilatory (VT) heart rate (HRT). During PXT, subjects pedaled at a prescribed power calculated from the GXT. Measures during PXT included gas analysis, HR and TE. Descriptive statistics, ANOVA and linear regressions for determining rate change during the PXT were performed. PXT measures indicated high intensity work output: HR= 181.6 (9.3) bpm; VO_2= 46.6 (7.1) ml/kg/min; RER = 1.1 (0.1); TE = 9.9 (4.2) min. These conclusions were established: 1) Low slope increases in VO_2 (0.07), VCO_2 (0.09), RER (0) and HR (2.1) show evidence of steady state; 2) values for VO_2, VCO_2, RER and HR during PXT, and the mean TE of ~10 min. indicate steady state; 3) thresholds and work beyond thresholds define a phase transition.

Key Words: Exercise Physiology, Performance

INTRODUCTION

Physiological thresholds generally describe, within a specific variable, an abrupt rate change with a proportionate change in workload (1,2,3). Commonly reported variables associated with a threshold are lactate, ventilation and heart rate (HR). The heart rate threshold (HRT) has been used as a non-invasive measure for determining the onset of limitations in myocardial function (4). There are reported relationships between the HRT and the lactate turn point (LTP) (5,6). In addition, it was reported through a meta-analytic procedure that lactate threshold and ventilatory threshold (VT) occurrences were not significantly different (7). There is also considerable research indicating the physiological associations between lactate accumulation and fatigue (1,4,8,9).

The literature describes the importance of threshold identification in performance as an indication of a level of work considered maximal steady state beyond which the indices of fatigue are soon realized (10,11,12). Yet thresholds measured in selected variables are inappropriately identified as specific points leading to the onset of fatigue. Anecdotal accounts during performance indicate athletes perform above this point for extended periods of time. Questions arise as to the ability of the human body to be able to establish steady state beyond threshold. It is hypothesized that physiological rate changes currently labeled as thresholds are more appropriately identified as "phase transitions", acutely adapting to the demands of high intensity work.

Phase transitions occur in complex systems (13). Complex systems (i.e., human body) are defined as systems in which there is a collection of interacting adaptive agents (13,14). Outside of exercise physiology, occurrences identified as phase transitions take place at a specific parameter value. This identification is similar to the detection of physiological thresholds. Because of interactions among physiological variables, as work increases it requires these variables to adapt to or transition to an increased or altered state. For example, with the onset of exercise there is an adaptive increase in HR, oxygen consumption and catecholamine secretion. Current research provides considerable speculation as to the disproportionate dynamics of physiological reactions at the point of threshold (3,5,8,9,10). While aforementioned anecdotal accounts have been noted, very little research has investigated the physiological reactions of the body to long-term work beyond this threshold point. The purposes of this study were twofold: 1) to determine non-invasive physiological kinetics during steady work beyond physiological threshold, and 2) to establish a paradigm where physiological threshold occurrences are viewed as phase transitions acutely adapting to greater workloads.

METHODS

Subjects

Nineteen cyclists (13 male and 6 female) ranging from 20 to 35 years of age participated in this study. Selected subjects were considered high-fit subjects who regularly trained on the bicycle a minimum of four days/week. Subjects were familiarized with the testing procedures and asked to abstain from caffeine beverages for at least 12 hrs and from strenuous physical activity and alcohol for at least 24 hrs before any scheduled test. In addition, all subjects were asked to be euhydrated upon arrival. Testing was approved by University IRB and all subjects signed an informed consent prior to testing.

Baseline

Prior to obtaining baseline measures, subjects completed a medical history questionnaire and the Par-Q™ Fitness Readiness Questionnaire. Pre-test measures included resting blood pressure (mmHg), skinfolds (% bodyfat), height (cm), weight (kg) and resting HR (beats/min).

Graded Exercise Test

Each subject performed a graded exercise stress test (GXT) to volitional fatigue using their own bicycle mounted on a magnetic resistance cycle ergometer. This test determined each subject's peak aerobic capacity, physiological thresholds and time to exhaustion (TE). During the GXT, the pedal frequency (rev/min) was chosen by the subject as the most comfortable and efficient for each workload. For males, the GXT began at 50 Watts and increased 50 Watts every two minutes until volitional fatigue. Females commenced the GXT at 50 Watts, with increases of 50 Watts every two minutes until the stage beyond 150 Watts. Thereafter, each additional stage increased 30 Watts every two minutes until volitional fatigue. These GXT protocols approximated a 25 Watts/min increase for males and 15 Watts/min increase for females. After reaching exhaustion, the cadence was reduced to a self-selected value and the workload was decreased below 100 Watts to facilitate active recovery. During the test, whole body oxygen consumption (VO_2) and carbon dioxide production (VCO_2) were quantified using breath-by-breath indirect calorimetry utilizing a ParVo Medics™

system. Heart rate was measured beat-by-beat utilizing a portable electronic telemetry system (Polar^{TM}), with beat-to-beat data expressed as beats/min for all analyses.

Performance Exercise Test

Immediately following the GXT subjects completed a 30 min active recovery period, and then performed a performance exercise test (PXT). During the active recovery period, subjects pedaled at a self-selected cadence that did not exceed 100 Watts and were allowed to hydrate ad libitum with water.

The exercise protocol for the PXT was determined during the active recovery from the GXT. The PXT power was determined as the median point between the power at ventilatory threshold (VT) and the power at volitional fatigue during the GXT. Ventilatory threshold was detected utilizing the V-slope method where VCO_2 increases disproportionately as VO_2 increases proportionately (11). As the subjects reached the prescribed power output, they maintained this workload in a steady state manner until volitional fatigue. Measurements during the PXT included gas analysis (VO_2, VCO_2, V_E, RER), HR and TE.

Statistical Analyses

Descriptive statistics included mean ± SD for subject demographics and resting GXT and PXT measures. Ventilatory threshold was reported as an absolute value (L/min) and relatively as %VO_2max. Heart rate threshold was detected by the logarithmic regression line of best-fit crossover with the linear regression line of best fit (15). Heart rate threshold was reported as an absolute value (beats/min), as VO_2 (L/min) and as a percent of maximal heart rate (HRmax). A Pearson Product R Correlation Coefficient was used to determine associations between variables. Linear regression analysis was run to provide a slope or rate change over time during the performance test for VO_2, VCO_2, RER and HR. By establishing low slope kinetics during high intensity work, an argument could be made for steady state beyond threshold. A randomized analysis of variance (ANOVA) provided bivariate analyses of slope values obtained during the performance test (i.e., VO_2, VCO_2, RER, HR) and for comparing thresholds expressed as absolute VO_2 (L/min). Power analysis of the design indicated that a sample size of 16-21 yielded high power (0.8 to 0.9) for an effect size of 0.8. Significance was set a priori at $p \pm 0.05$.

RESULTS

Descriptive statistics of the subjects are presented in Table 1, and reveal the endurance trained status of the subjects (12). Table 2 displays the results of the PXT. The goal of the PXT was to maintain subject work output at a high-intensity, steady state beyond the VT until volitional fatigue. The values, specifically %VO_2max and %HRmax, presented in Table 2 suggest the subjects performed at a very high intensity of work during the PXT. The TE of 9.7 ± 4.3 minutes suggest a steady state during the constant prescribed workload. Table 3 displays the calculated slopes of the variables measured during the performance test. Slopes were established to determine variable rate change for analysis of steady state. The low slope values given in percentages shown in Table 3 and Figure 1, coupled with the TE suggest a steady state during the PXT.

Table 1. Resting and Maximal Test Values

Variable	*Mean ±SD*
Age (yr)	24.9 ± 5.3
Height (cm)	175.6 ± 9.8
Weight (kg)	70.6 ± 12.1
Body-fat (%)	13.2 ± 5.9
VO_2max (ml/kg/min)	58.3 ± 8.2
HR max (beats/min)	191.6 ± 8.4
Ventilatory Threshold (%VO_2max)	74.6 ± 10.4
Heart Rate Threshold (% HR max)	89 ± 3.0

Figure 2 shows an individual response indicative of the participants' HR responses during the PXT, and Figure 3 shows a profile of one subject's RER values.

Table 2. Values Obtained during the Performance Exercise Test

Variable	*Mean ±SD*
VO_2 (L/min.)	3.4 ± 0.76
VO_2 (ml/kg/min)	47.6 ± 6.8
Percent (%) VO_{2max}	82.1 ± 10.3
VCO_2 (L/min.)	3.7 ± 0.82
Respiratory Exchange Ratio (RER)	1.1 ± 0.06
Heart Rate (beats/min.)	181.4 ± 9.8
Percent (%) Heart Rate$_{max}$	94.8 ± 5.0
Time to Exhaustion (min)	9.7 ± 4.3

Table 3. Slopes of Variables during the Performance Exercise Test

Variable	*Mean ±SD Slope (%)*
VO_2	0.068 ± 0.07
VCO_2	0.096 ± 0.11
Heart Rate	2.1 ± 1.7
RER	- 0.001 ± 0.02

When analyzing the slope differences between variables during the PXT a randomized ANOVA was performed. The results indicated that while slopes did differ, the expired gas slopes of VO_2 versus VCO_2 showed no significant differences. Yet the aforementioned expired gas slopes when compared to the HR and RER slopes were shown to be significantly different.

There were no significant associations between rate changes during the PXT and VO_{2max} established during the GXT. Also, there were no significant associations between TE and rate change of any of the variables. The rate change variables that showed associations were VO_2 vs. VCO_2 ($p < 0.01$) and VO_2 vs. HR ($p < 0.01$).

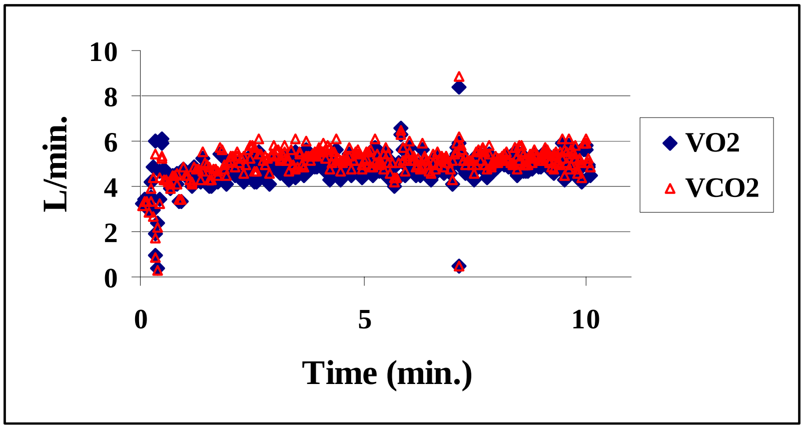

Figure 1. Gas analysis profile of one subject during the performance exercise test.

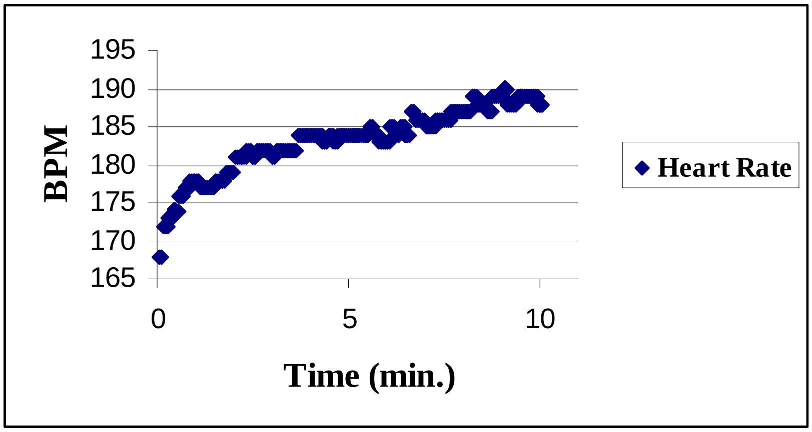

Figure 2. Heart rate profile of one subject during the performance exercise test.

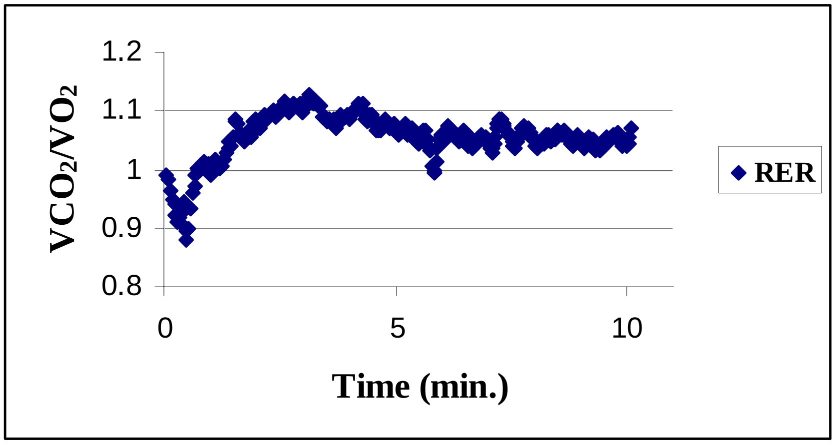

Figure 3. Respiratory exchange ratio of one subject during the performance exercise test.

DISCUSSION

The literature indicates there are several physiological thresholds that define moments at which variable rate change is disproportionate to the increases in workload. While these points may accurately be termed thresholds by definition, synonymous definitions of the "onset of fatigue" as well as the point of "maximal steady state" are spurious (6,10,11). While the concepts of "onset of fatigue" and "maximal steady state" may be applicable during GXT, this study indicted that subjects could cycle at intensities well beyond threshold at steady state. In relation to the current study, steady state work beyond threshold would indicate an acute adaptation (i.e., modification) of reactions to sustain this level of work output. In physical systems, defined phase transitions occur when systems undergo modification as a result of an external parameter increasing beyond a critical value (13). The purpose of the current study was to determine variable profiles during workloads well above threshold prior to volitional fatigue and ascertain if these profiles described a phase transition.

The results indicate that the subjects were working at a high intensity during the PXT, with VO_2 at 82% and HR at 95% of maximal VO_2 and HR, respectively. Yet the VT and HR thresholds identified during the GXT were at 75% and 89% of maximal VO_2 and HR, respectively. According to threshold definitions, the subjects should have fatigued in a short period of time without establishing a new steady state (9). Because the subjects did eventually fatigue, it is speculated that changes in intramuscular pH contributed to the peripheral fatigue and eventual time to exhaustion. This speculation is supported by Whipp (16), who studied the influence of peripheral chemoreceptors on exercise hyperpnea. Whipp noted that during a GXT there is a partially compensated metabolic acidosis with slow increments of work rate increases beyond threshold. Investigating the slopes of the variables and TE one sees evidence of steady state and phase transition. Figure 1 shows one subject's response, indicative of the profiles seen in VO_2 and VCO_2 during the PXT. Theoretically this profile would differ considerably should threshold truly be the onset of fatigue. Accordingly, VCO_2 would continue to increase exponentially with a concomitant increase, then plateau of VO_2 (11). As indicated in Figure 1, and Table 3, the slopes of VO_2 and VCO_2 were not significantly different from each other.

A similar profile can be seen in the HR response during the PXT. Figure 2 shows an individual response indicative of the participants' HR responses during the PXT. Even though the HR profiles were of a greater slope than other variables, the rate of increase was considerably low when compared to HR responses during the GXT. This is not surprising considering the continual change in workload during the GXT.

The profile seen in Figure 2 has a heart rate range of just over 10 beats/min for the entire PXT but only varies by 5 beats/min for the last 5.5 minutes of the test. The low slope profile of HR is similar to that seen during lower intensity, long duration efforts. While slope profiles differed between some variables (i.e., VO_2 vs. HR), the rate change indicated characteristics of steady state (6, 10, 17). In his research on exercise hyperpnea in humans, Whipp noted three temporal phases: (1) the initial rapid response, (2) the slower, exponential increase, and (3) the steady state phase (16). Of interest in the description of these phases is that during phase II, or the slower phase, it is marked by an exponential increase with concomitant separation of the VO_2 and VCO_2 kinetics. Yet phase III, or the steady state phase is marked by CO_2 levels being regulated. Profiles from this study indicate that phase III kinetics describe those found in the current study.

In reflecting on steady state one finds rather vague descriptions in relation to physiological responses. Definitions widely accepted within the field describe steady state as a condition of dynamic constancy and/or a balance between metabolic demands and responses (2,3). Lacking in these definitions and in the research literature is a definitive timeline for consideration of steady state. Taking the two aforementioned definitions one could conclude that steady state is a metabolic balance with a range of dynamic fluctuation. From this, it may be surmised that during constant loads at high intensities, the body attempts to balance metabolic demands through physiological reactions and interactions. It is not surprising that during GXT tests where workloads are continually increased this point of threshold is seen as the onset of fatigue. If however the threshold points were truly the onset of fatigue, expired gas profiles beyond threshold, even during steady work demands would indicate a greater increase in VCO_2 compared to VO_2.

Physiologically, one could measure this hypothetical definition of steady state through the measure of respiratory exchange ratio (VCO_2/VO_2). Generally speaking, with oxygen consumption keeping pace with carbon dioxide production there would be a steady ratio of 1. The literature notes this value as high intensity work with the primary source of ATP production being provided via near complete carbohydrate oxidation via the glycolytic pathway and mitochondrial respiration (1, 2, 4). Above an RER of 1, CO_2 is being produced at a rate greater than O_2 consumption and fatigue soon ensues. Figure 3 shows a profile of one subject's RER values. This profile indicates the ratio is above 1 for an extended period of time, yet from minutes 6 through 10 remains at a steady value. This response is atypical and inconsistent with how non-steady state exercise is assumed to occur above threshold intensities.

The interaction of various systems (i.e., cardiovascular, neuromuscular) to maintain the PXT of this study for an extended period of time is a phase transition. It describes all systems as actively reacting to a change in environmental conditions when perturbed (14). Once perturbed, the system seeks a new level of equilibrium (i.e., steady state) until another disturbance occurs.

CONCLUSION

The non-invasive measures of HR and expired gases have provided a profile for high intensity work beyond threshold. These profiles and the time to exhaustion indicate the subjects achieved a level of steady state during a cycling performance test. Because steady state is ill-defined in terms of time, one could argue that while the physiological profiles seen in this study are near equilibrium, the mean time to exhaustion of 9 minutes does not constitute a steady state. There are many mechanisms of fatigue facilitating an individuals' time to exhaustion. In long duration bouts of exercise at steady state this mechanism may be in the form of a depleted energy source (e.g., glycogen). At higher intensities, these mechanisms are generally associated with metabolite accumulation. Further investigation of high intensity fatigue mechanisms is warranted during periods of high intensity steady state. The physiological profiles in the current study provide an argument refuting standard definitions of threshold as the "onset of fatigue" and the point of "maximal steady state". In addition, these profiles provide evidence that as one works beyond threshold for a period of time, metabolic transitioning to meet the demands of a higher workload occurs. While threshold occurrences are recognized during protocols with continued increasing work rates, the application of the concepts of fatigue and maximal steady state should be re-addressed. A future paradigm provided by the current research in conjunction with thresholds identifies these reactions as points of phase transition accommodating greater workloads.

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