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Original Research

Comparisons of the Metabolic Intensities at Heart Rate, Gas Exchange, and Ventilatory Thresholds

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ABSTRACT

International Journal of Exercise Science 13(2): 455-469, 2020. PURPOSE: This study compared the $\dot{V}O_2$ corresponding to the critical heart rate (CHR$\dot{V}O_2$) and the physical working capacity at the heart rate fatigue threshold (PWC$_{hrt}\dot{V}O_2$) to the gas exchange threshold (GET), ventilatory threshold (VT), and respiratory compensation point (RCP). METHODS*:* Nine runners (mean ± SD, age 23 ± 3 years) completed an incremental test on a treadmill to determine $\dot{V}O_{2peak}$, GET, VT, and RCP. The CHR$\dot{V}O_2$ and PWC$_{hrt}\dot{V}O_2$ were determined from 4 separate constant velocity treadmill runs to exhaustion and HR and time to exhaustion were recorded. Differences among the thresholds were examined with a one-way repeated measures ANOVA ($p \leq 0.05$). RESULTS: The GET (38.44 mL·kg^{-1}·min^{-1}, 78% $\dot{V}O_{2peak}$), VT (37.36 mL·kg^{-1}·min^{-1}, 76% $\dot{V}O_{2peak}$), and PWC$_{hrt}\dot{V}O_2$ (38.26 mL·kg^{-1}·min^{-1}, 77% $\dot{V}O_{2peak}$) were not different, but were lower than the RCP (44.70 mL·kg^{-1}·min^{-1}, 90% $\dot{V}O_{2peak}$; $p = 0.010$, $p < 0.001$, $p = 0.001$, respectively). The CHR$\dot{V}O_2$ (40.09 mL·kg^{-1}·min^{-1}, 81% $\dot{V}O_{2peak}$) was not different from the GET ($p = 1.000$), VT ($p = 0.647$), PWC$_{hrt}\dot{V}O_2$ ($p = 1.000$), or RCP ($p = 0.116$). CONCLUSIONS: These results indicated that the initial metabolic intensities at CHR and PWC$_{hrt}$ lie within the heavy and moderate intensity domains, respectively. Therefore, the PWC$_{hrt}$ may provide a relative intensity more appropriate for untrained populations, while the CHR may be more appropriate for more trained populations.

KEY WORDS: Critical heart rate, endurance training, critical power, PWC$_{hrt}$, fatigue thresholds

INTRODUCTION

Gaesser and Poole (1996), and Francis et al. (2010) have described three exercise intensity domains, moderate, heavy, and severe, which are defined by distinct physiological responses. For continuous exercise performed within the moderate domain, $\dot{V}O_2$ reaches a steady state within ~3 min, without the appearance of the $\dot{V}O_2$ slow component, and there is no increase in blood lactate concentration (21). Within the heavy exercise intensity domain, there is a delayed steady-state response for both $\dot{V}O_2$ and blood lactate that stabilizes within 10 to 20 min. The gas exchange (GET) and ventilatory (VT) thresholds demarcate the moderate from heavy exercise intensity domains and reflect the highest intensity that can be sustained with reliance primarily on aerobic ATP reconstitution (21). Critical power (CP) is defined as the asymptote of the power duration curve, demarcates the heavy from severe domain, and reflects the highest intensity where $\dot{V}O_2$ and blood lactate responses stabilize (21). Within the severe intensity domain, the onset of fatigue occurs rapidly. Although there is conflicting evidence (7, 42), severe exercise intensities result in a large $\dot{V}O_2$ slow component and $\dot{V}O_2$ is driven to $\dot{V}O_{2max}$ at exhaustion (21). Similarly, blood lactate concentration does not stabilize as the bicarbonate buffering system is overwhelmed (2, 39). Bergstrom et al. (2013) reported that the respiratory compensation point (RCP) and CP occur at the same intensity, and, therefore, both thresholds can be used to demarcate the heavy and severe domains.

Exercise programs for improving cardiorespiratory endurance are typically prescribed at a percentage of maximal heart rate (HR) or $\dot{V}O_{2max}$ (or reserve) that can be sustained for 20 to 60 minutes and elicit the desired metabolic and cardiorespiratory responses (22, 38). The threshold (% HR or $\dot{V}O_{2max}$) for improving cardiorespiratory fitness is dependent upon an individual's training status, where intensities of 65–80% $\dot{V}O_{2max}$ in moderately trained individuals, and 95 – 100% $\dot{V}O_{2max}$ in highly trained individuals may be required to elicit adaptations (29). These intensity dependent responses are associated with performance of exercise sessions within specific domains (moderate, heavy, severe) that are defined by fatigue thresholds (GET, VT, or RCP). For example, Daniels (1989) identified 5 intensities commonly used for cardiorespiratory endurance training that are hypothesized to correspond to the moderate, heavy, and severe intensity domains. Specifically, the easy pace is prescribed at ~70% $\dot{V}O_{2peak}$ for one interval that can easily be sustained for 60 min. Therefore, the easy pace likely reflects a moderate exercise intensity, below the GET and VT. The marathon and threshold paces are prescribed at ~85% $\dot{V}O_{2peak}$ and are either performed for one interval that is shorter in duration (< 60 min), but at a higher intensity than an easy run (marathon pace), or for multiple intervals between 5 and 10 min (threshold pace). The marathon and threshold paces likely reflect exercise within the heavy intensity domain, above the GET and VT, but below the RCP. Lastly, the interval pace reflects ~95-100% $\dot{V}O_{2peak}$ and is performed for multiple intervals of 2 to 5 minutes at ≥ 5K race pace and the repetition pace performed at an intensity > 100% $\dot{V}O_{2peak}$ for multiple, 30 to 90s intervals (13, 25). Thus, the interval and repetition paces likely reflect severe intensity exercise performed above the RCP. Successful cardiorespiratory endurance training protocols have utilized combinations of these paces to increase $\dot{V}O_{2peak}$, anaerobic threshold, and improve running economy (1, 34). However, the relative intensities (percent $\dot{V}O_{2max}$) where the GET, VT, and RCP occur are, in part, dependent upon training status (26, 43) and may not be accurately reflected by the percentages of $\dot{V}O_{2peak}$ used to define these training intensities. Thus, these paces are estimates based on past performances, and therefore, do not provide a true individualized response that can accurately be used for training. Therefore, a need exists for individualized intensities that can provide an adequate training stimulus to elicit improvements in cardiorespiratory endurance.

The recent application of HR to the critical power (CP) model to derive the critical heart rate (CHR) (32) may provide an individualized, physiologically based threshold that meets the intensity (83-94% HR of $\dot{V}O_{2peak}$) (5) and duration (> 24 min) recommendations for cardiorespiratory endurance training. The CHR represents the highest HR that can be maintained for an extended period of time without fatigue, and has been shown to reflect a similar initial HR as the HR at the RCP. Thus, the CHR may provide a HR estimate that reflects the demarcation of the heavy and severe intensity domains (32) at the beginning of exercise. However, when exercise is anchored by a physiological parameter, such as HR, there are dissociations in physiological variables that are commonly thought to increase with time to exhaustion (7). Constant HR exercise requires a gradual decrease in velocity or power output to maintain HR. Therefore, parameters such as $\dot{V}O_2$ decrease along with the decreasing workload (5, 6, 31). As a result, constant HR exercise at the CHR has consistently been shown to be sustainable for greater than 30 min, with ranges in time to exhaustion (T_{Lim}) of ~47 to 60 min, compared to constant power output exercise at CP that has been sustained for as little as 6.3 min up to 60 min (3, 4, 8, 10). In addition, previous researchers have indicated that the decrease in intensity (metabolic rate and velocity or power output) required to maintain a constant HR during continuous exercise at the CHR is small enough to maintain the desired $\dot{V}O_2$ responses recommended for physiological adaptations (5, 6, 31). Thus, the CHR may provide a useful, individualized training intensity for exercise prescription at a constant HR.

The necessity remains, however, for a threshold that reflects an intensity that will lead to improvements in cardiorespiratory endurance for sedentary or untrained populations, as the CHR (83-94% HR_{max}) (5) reflects an intensity that is greater than the intensities typically recommended (57-63% HR_{max}) (38) for those populations. The physical working capacity at the fatigue threshold (PWC_{ft}) was originally developed as a submaximal test and used to evaluate the exercise capacities of older adults (18). The PWC_{ft} identifies the point of neuromuscular fatigue from a series of submaximal (19) or maximal tests where the slope coefficients of electromyographic amplitude (EMG) versus time are measured, and then plotted against power output. The y-intercept of the power output vs slope coefficient was then defined as the highest power output that does not result in an increase in EMG amplitude (muscle activation) over time (17). Wagner et al. (1993) applied the PWC_{ft} model to HR to provide the physical working capacity at the heart rate threshold (PWC_{hrt}), where HR replaced EMG amplitude. Therefore, theoretically, the PWC_{hrt} represents the highest velocity or power output that does not cause an increase in HR greater than 0.1 beats·min^{-1} over time, which was identified as an intensity that could be sustained for an 8-hour work day (41, 44). Additional work has shown the velocity at the PWC_{hrt} to be located within the moderate intensity domain (33). Furthermore, studies have shown that the PWC_{hrt} is sensitive to cardiorespiratory endurance training programs (45), and that training at a moderate intensity produced increases in $\dot{V}O_{2max}$, improved vascular function, and decreased body fat percentage (27, 35, 37) in previously sedentary populations. Therefore, the PWC_{hrt} may provide an individualized, sustainable intensity that is high enough to stimulate adaptations for sedentary populations beginning an exercise program.

The CHR and the PWC_{hrt} may be used to provide an individualized, sustainable estimate of the desired intensity of exercise for cardiorespiratory endurance training programs, without the need to measure gas exchange parameters for the determinations of $\dot{V}O_{2peak}$ or ventilatory and gas exchange thresholds. The CHR and PWC_{hrt} are identified as a HR and velocity (or power output), respectively, and, thus, it is unclear where the initial metabolic intensity of these thresholds lies relative to the exercise intensity domains. Identifying the initial metabolic intensity ($\dot{V}O_2$) associated with the CHR (CHR$\dot{V}O_2$) and PWC_{hrt} ($PWC_{hrt}\dot{V}O_2$) may allow for the determination of the utility of using these thresholds for cardiorespiratory endurance training programs for individuals of varying training status (22, 38). Furthermore, the metabolic intensity may transverse the traditional exercise intensity domains during exercise at a constant HR. Thus, it is important to identify a HR threshold that is low enough to be sustained for at least 20 min, but high enough to elicit the desired metabolic stimulus. Therefore, the purposes of this study were to: 1) compare the initial metabolic ($\dot{V}O_2$) intensities of the CHR and PWC_{hrt} to the GET, VT, and RCP used to define the exercise intensity domains; and 2) make inferences regarding the utility of these thresholds for cardiorespiratory endurance training by comparing the relative metabolic intensities to those that describe commonly used training paces.

METHODS

Participants

Nine moderately trained, recreational runners (6 males, and 3 females, mean ± SD, age 23 ± 3 years, height 174 ± 8 cm, and weight 72 ± 13 kg) were recruited for this study. Moderately trained was defined as running 16-48 km $\cdot$week^{-1} for at least six months prior to enrollment in this study (38). These subjects were from a large data set that included multiple independent and dependent variables. The derivation of the PWC_{hrt} and its comparison to metabolic rate at other fatigue thresholds in this study were not available in previously published papers (5, 6, 7). The subjects were instructed to avoid consuming caffeine for 4 hours prior to testing and to avoid exercise 24 hours before testing. All subjects were screened for known cardiovascular, pulmonary, metabolic, muscular, and/or coronary heart disease. This study was approved by the University Institutional Review Board for Human Subjects, IRB# 20130313412EP. All subjects completed a health history questionnaire and signed a written informed consent document before testing.

Protocol

This study involved a total of five visits, separated by 24-72 hours. The GET, VT, and RCP were determined from an incremental treadmill test to exhaustion. Subsequently, HR was measured during four, randomly ordered, constant velocity runs to exhaustion at ~81-102% of the velocity corresponding to $\dot{V}O_{2peak}$ ($v\dot{V}O_{2peak}$). The CHR was derived from the slope of the total heartbeats versus time to exhaustion relationship as previously described (32). The PWC_{hrt} was derived from the four, constant velocity runs and was defined as the highest velocity that does not elicit an increase in HR over time (zero slope). The corresponding $\dot{V}O_2$ for the CHR and PWC_{hrt} was derived by plotting $\dot{V}O_2$ versus HR and velocity, respectively, from the incremental treadmill test.

Determination of GET, VT, and RCP: Each subject performed an incremental treadmill (Precor Inc., Bothell, WA, USA) test to exhaustion to determine the $\dot{V}O_{2peak}$, GET, VT, and RCP. A 3-minute warm-up was performed on the treadmill at 4.8 km$\cdot$hr^{-1} and 0% grade, followed by 3 minutes passive recovery. Following the warm-up, the subjects were fitted with a nose clip and breathed through a two-way valve (Hans Rudolph 2700 breathing valve, Kansas City, MO, USA). Expired gas samples were collected and analyzed using a calibrated TrueMax 2400 metabolic cart (Parvo Medics, Sandy, UT, USA). The gas analyzers were calibrated with room air and gases of known concentration prior to all testing sessions. The O_2 and CO_2 were recorded breath by breath and expressed as 20 second averages (40). Heart rate was continuously recorded and also expressed as 20 second averages using a Polar Heart Rate Monitor (Polar Electro Inc., Lake Success, NY), which was synchronized to the metabolic cart. The incremental test started with a velocity of 6.4 km·hr^{-1} with a 0% grade. As the test progressed, the velocity was increased by 1.6 km·hr^{-1} every 2 minutes until 14.4 km·hr^{-1}. Once the 14.4 km·hr^{-1} stage was reached, the velocity was no longer increased, and the grade was increased 2% every 2 minutes until the subject could no longer maintain the running velocity and grasped the handrails to indicate exhaustion (28). The subjects were deemed to have met the criteria for a maximal effort if they obtained at least 2 the following criteria: RER ≥ 1.1, HR ≥ ± 10 beats·min^{-1} age predicted HR_{max}, and RPE > 17. The $\dot{V}O_{2peak}$ was defined as the highest 20 second average $\dot{V}O_2$ measured during the test (40). The GET was determined using the V-slope method, where the GET was defined as the $\dot{V}O_2$ corresponding to the point of intersection of two separately derived regression lines of the $\dot{V}O_2$ versus $\dot{V}CO_2$ plot (Figure 1). The VT (Figure 2) and RCP (Figure 3) were determined using the same method, with the exception of using the $\dot{V}_E$ versus $\dot{V}O_2$ plot, and $\dot{V}_E$ versus $\dot{V}CO_2$ plot, respectively.

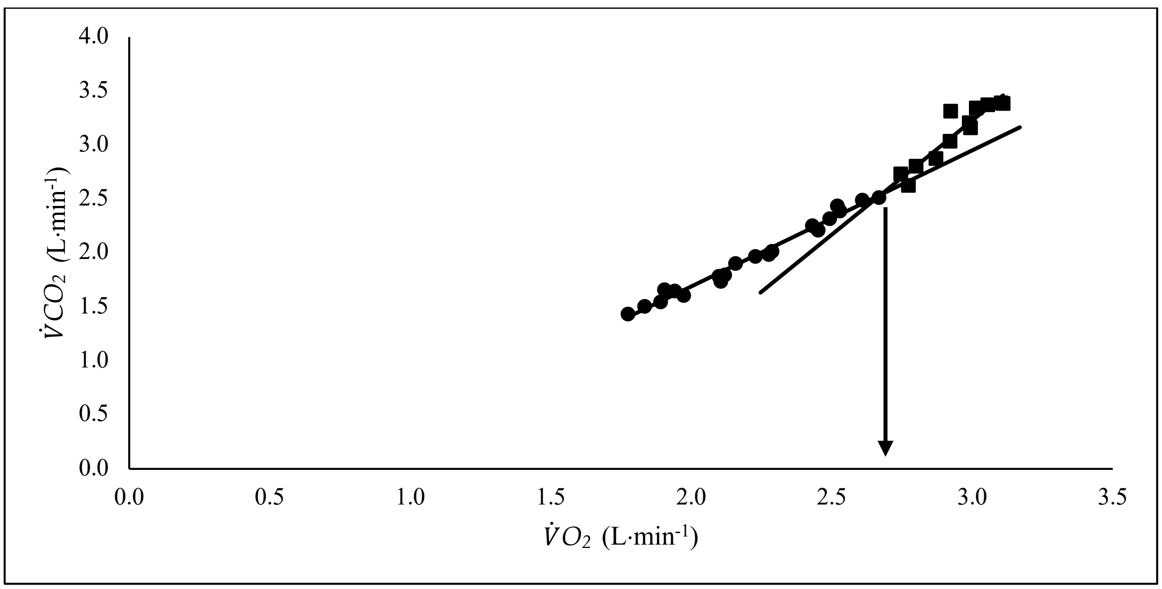

Figure 1. Example of the gas exchange threshold (GET) determination for a representative subject. The GET was defined as the breakpoint in the $\dot{V}CO_2$ (L·min^{-1}) versus $\dot{V}O_2$ (L·min^{-1}) graph.

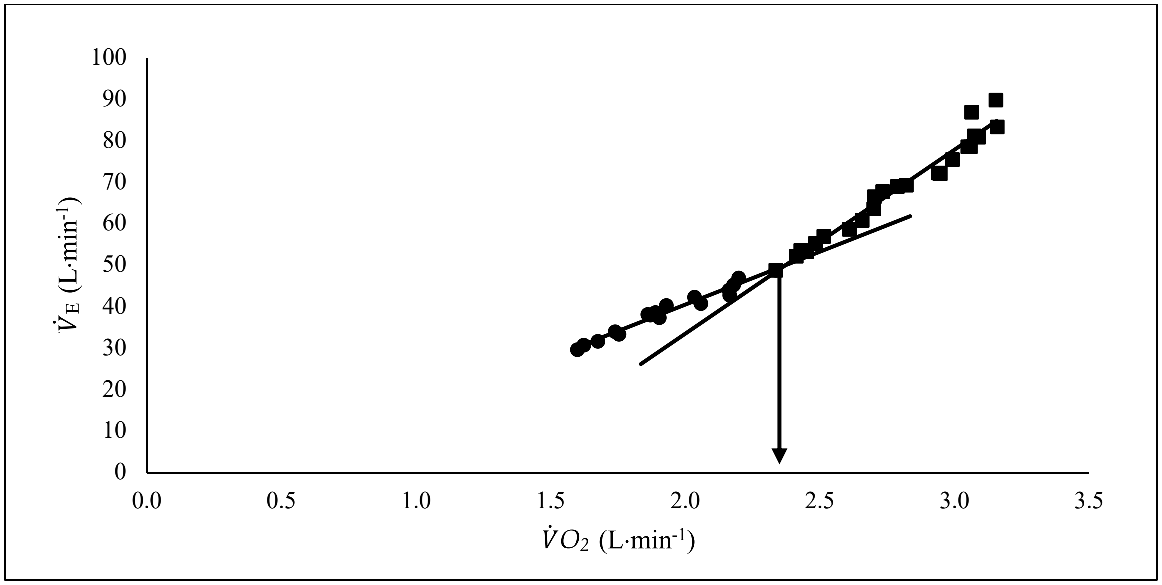

Figure 2. Example of the ventilatory threshold (VT) determination for a representative subject. The VT was defined as the breakpoint in the $\dot{V}_E$ (L·min^{-1}) versus $\dot{V}O_2$ (L·min^{-1}) graph.

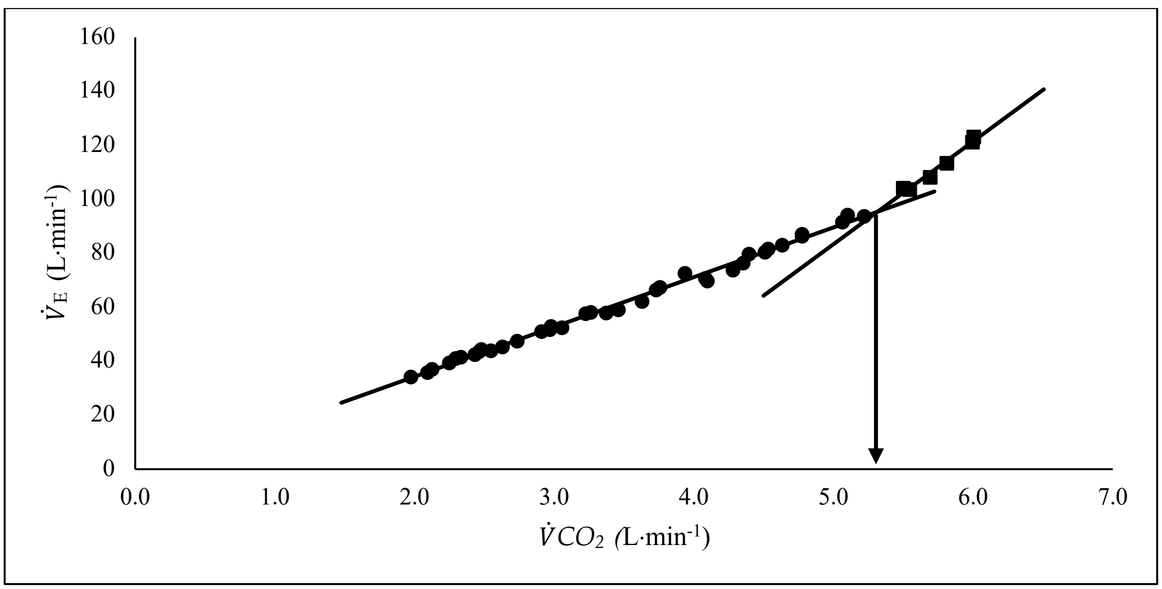

Figure 3. Example of the respiratory compensation point (RCP) determination for a representative subject. The RCP was defined as the breakpoint in the $\dot{V}_E$ (L·min^{-1}) versus $\dot{V}CO_2$ (L·min^{-1}) graph.

Determination of the CHR: The subjects completed 4 different constant velocity treadmill runs to exhaustion (T_{Lim} = 6.95-22.25 min) at percentages of $v\dot{V}O_2$ (81-102%) with each trial separated by at least 24 hours. All of the subjects completed a 5-minute warmup at a self-paced velocity and practiced getting onto the treadmill at the designated velocity prior to each trial, followed by 3 minutes of rest. Timing began once the subject released the handrails and was terminated when they reached for the handrail to signal exhaustion. Throughout each run, HR was constantly recorded and expressed as 5 second averages. The total heart beats (HB_{Lim}) were calculated by taking the product of the time to exhaustion (T_{Lim}) and the average 5 second HR.

The CHR ($b \cdot min^{-1}$) was determined as the slope of the linear regression line of the plot of the HB_{Lim} versus the T_{Lim} for each velocity (Figure 4). The $\dot{V}O_2$ corresponding to the CHR ($b \cdot min^{-1}$) (CHR$\dot{V}O_2$) was determined for each subject from the $\dot{V}O_2$ versus HR relationship from the incremental test.

Determination of the PWC_{hrt}: The 5-second average HRs from the four, constant velocity runs were plotted versus time to derive the slope coefficients of the linear regression for each velocity. The PWC_{hrt} was derived by first plotting the 5-second average HRs versus time for each of the four, constant velocity, exhaustive runs (Figure 5A). The initial rapid rise in HR during the first 3-minutes of the runs were removed to account for the initial cardiac adjustment to the exercise. The velocities were then plotted as a function of the slope coefficients for the HR versus time relationship (Figure 5B). The PWC_{hrt} was defined as the y-intercept of the velocity versus slope coefficient relationship (HR versus time) and, theoretically, corresponds to the velocity at which there would be no increase in HR over time. The $\dot{V}O_2$ corresponding to the PWC_{hrt} ($km \cdot hr^{-1}$) ($PWC_{hrt}\dot{V}O_2$) was determined for each subject from the $\dot{V}O_2$ versus velocity relationship from the incremental test.

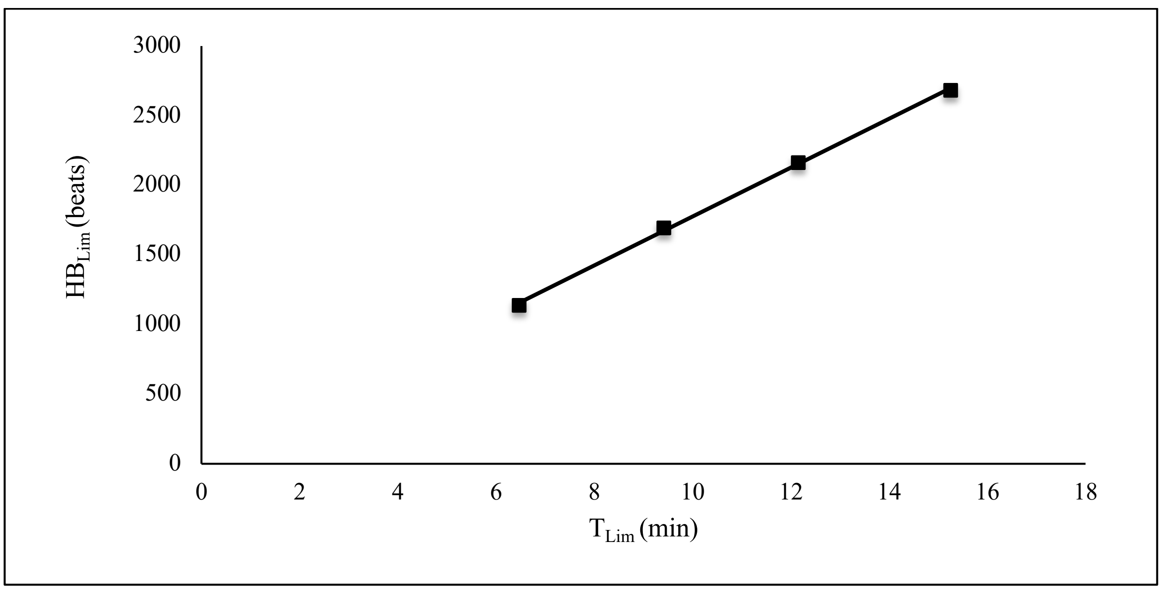

Figure 4. Example derivation of critical heart rate (CHR) for a representative subject. CHR is defined as the slope of the linear regression line of the total heart beats (HB_{Lim}) versus limit time (T_{Lim}).

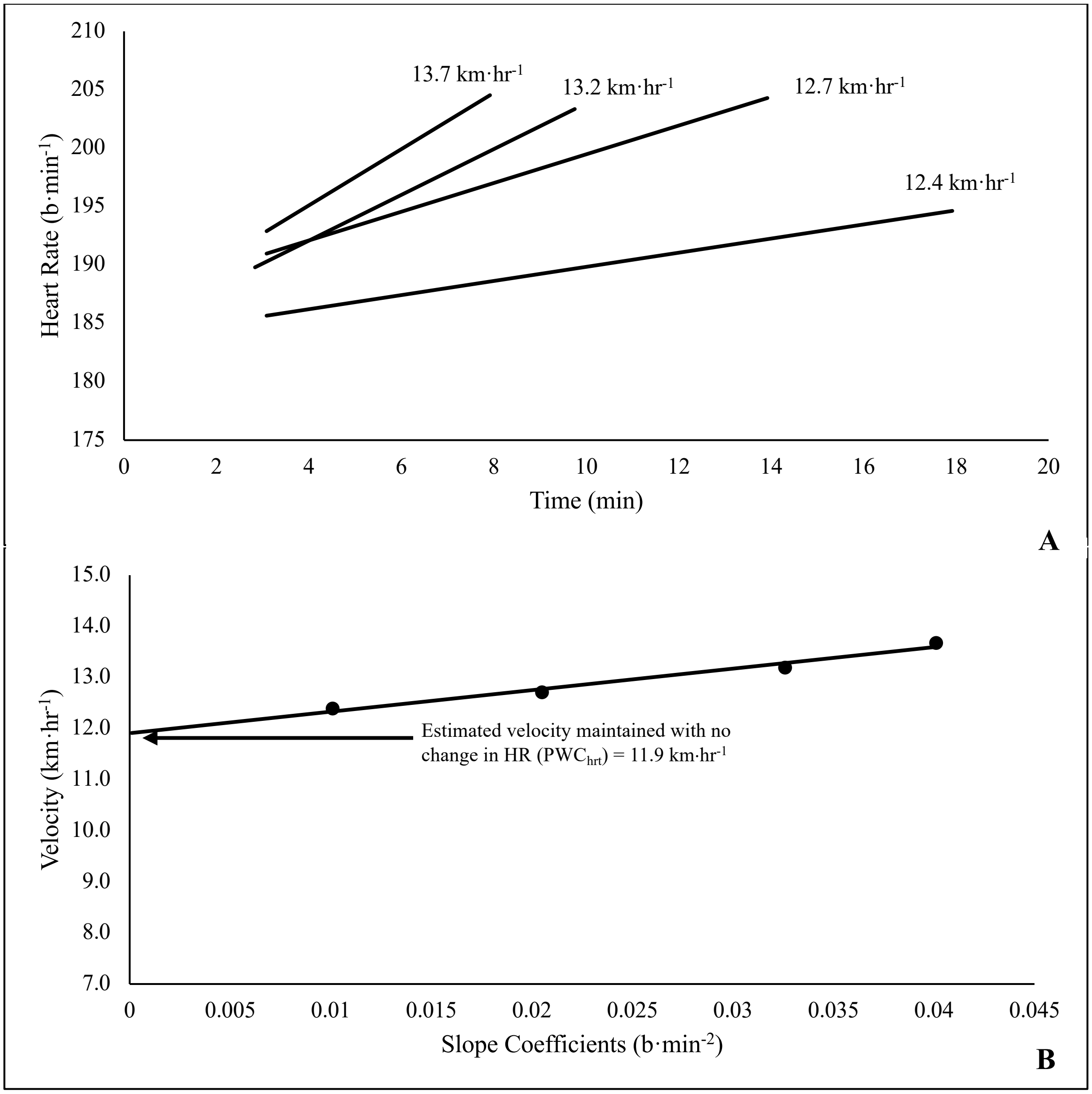

Figure 5A. Example of the determination of the physical working capacity at the heart rate threshold (PWC_{hrt}) for a representative subject. First the slope coefficients were derived from the heart rate ($b \cdot min^{-1}$) versus time (min) to exhaustion relationship for four, constant velocity runs. **Figure 5B.** The PWC_{hrt} was defined as the y-intercept of the velocity ($km \cdot hr^{-1}$) versus slope coefficients relationship for each velocity.

Statistical Analysis

The $\dot{V}O_2$ at each threshold (GET, VT, RCP, CHR$\dot{V}O_2$, and $PWC_{hrt}\dot{V}O_2$) was compared using a one-way repeated-measures ANOVA with post hoc Bonferroni corrected pairwise comparisons ($p \leq 0.005$). The 95% confidence intervals and effect sizes using Cohen's d were calculated for each threshold comparison. A zero-order correlation (Pearson product-moment) matrix was used to examine the relationships among the thresholds. The alpha level was set at $p \leq 0.05$ for the ANOVA and zero-order correlation statistical tests. The statistical analyses were performed using Statistical Package for the Social Science software (IBM SPSS Inc., Chicago, Illinois, USA).

RESULTS

The $\dot{V}O_{2peak}$ (mean ± SD) was 49.55 ± 5.32 mL·kg^{-1}·min^{-1} (range = 40.46 - 57.41 mL·kg^{-1}·min^{-1}) and the $v\dot{V}O_{2peak}$ was 15.87 ± 1.22 km·hr^{-1} (range = 14.27 – 17.97 km·hr^{-1}). The mean ± SD, range, and %$\dot{V}O_{2peak}$ for each of the thresholds (GET, VT, RCP, CHR$\dot{V}O_2$, PWC$_{hrt}\dot{V}O_2$) are listed in Table 1. The results of the one-way repeated-measures ANOVA indicated there were differences among the $\dot{V}O_2$ values corresponding to the thresholds (F = 12.504; p < 0.001; pη^2 = 0.610). The follow-up pairwise comparisons indicated the GET, VT, and PWC$_{hrt}\dot{V}O_2$ were not significantly different, but were lower than the RCP (Table 1). The CHR$\dot{V}O_2$, however, was not different from the GET, VT, RCP, or PWC$_{hrt}\dot{V}O_2$. Table 2 includes the mean differences among the thresholds as well as the 95% confidence intervals, p-values, and effect sizes for each comparison. The Pearson product-moment zero-order correlations (Table 3) showed the CHR$\dot{V}O_2$ and the PWC$_{hrt}\dot{V}O_2$ were significantly related to the VT and RCP, but not the GET.

Table 1. Mean ± SD, range, and %$\dot{V}O_{2peak}$ for each of the thresholds determined from the incremental treadmill test and constant velocity runs.

	Mean±SD (mL·kg^{-1}·min^{-1})	Range (mL·kg^{-1}·min^{-1})	% $\dot{V}O_{2peak}$
GET	38.44±4.31	31.50 - 44.94	78%±7
VT	37.36±3.62	30.34 - 41.93	76%±4
RCP	44.70±4.95*	37.65 - 53.57	90%±4
CHR$\dot{V}O_2$	40.09±5.64	32.24 - 48.47	81%±6
PWC$_{hrt}\dot{V}O_2$	38.26±3.47	32.41 - 44.10	77%±4

GET = gas exchange threshold, VT = ventilatory threshold, RCP = respiratory compensation point, CHR$\dot{V}O_2$ = the $\dot{V}O_2$ at the critical heart rate, PWC$_{hrt}\dot{V}O_2$ = the $\dot{V}O_2$ at the physical working capacity at the heart rate threshold. *significantly greater than GET, VT, and PWC$_{hrt}\dot{V}O_2$ (p < 0.05)

Table 2. The mean differences among the thresholds as well as the 95% confidence intervals (95% CI), p-values, and effect sizes (Cohen's d) for the for each comparison.

	Mean Difference (mL·kg^{-1}·min^{-1})	95% CI	p-value	Effect Size
GET vs. VT	1.082	-2.376 – 4.540	1.000	0.272
GET vs. RCP	-6.258	-11.032 – -1.483	0.010	1.348
GET vs. PWC$_{hrt}\dot{V}O_2$	0.180	-4.012 – 4.372	1.000	0.046
GET vs. CHR$\dot{V}O_2$	-1.648	-8.171 – 4.876	1.000	0.328
VT vs. RCP	-7.340	-10.803 – -3.877	<0.001	1.693
VT vs. PWC$_{hrt}\dot{V}O_2$	-0.902	-3.608 – 1.804	1.000	0.255
VT vs. CHR$\dot{V}O_2$	-2.730	-7.619 – 2.159	0.647	0.576
PWC$_{hrt}\dot{V}O_2$ vs. RCP	-6.438	-9.716 – -3.160	0.001	1.506
PWC$_{hrt}\dot{V}O_2$ vs. CHR$\dot{V}O_2$	-1.828	-6.616 – 2.960	1.000	0.390
CHR$\dot{V}O_2$ vs. RCP	-4.610	-10.032 – 0.812	0.116	0.868

GET = gas exchange threshold, VT = ventilatory threshold, RCP = respiratory compensation point, CHR$\dot{V}O_2$ = the $\dot{V}O_2$ at the critical heart rate, PWC$_{hrt}\dot{V}O_2$ = the $\dot{V}O_2$ at the physical working capacity at the heart rate threshold.

Table 3. Zero-order correlation matrix for the GET, VT, CHR$\dot{V}O_2$, and PWC$_{hrt}\dot{V}O_2$.

	GET	VT	RCP	CHR$\dot{V}O_2$
VT	0.781*			
RCP	0.682*	0.844*		
CHR$\dot{V}O_2$	0.501	0.742*	0.686*	
PWC$_{hrt}\dot{V}O_2$	0.664	0.822*	0.872*	0.762*

GET = gas exchange threshold, VT = ventilatory threshold, RCP = respiratory compensation point, CHR = critical heart rate, PWC$_{hrt}$ = Physical working capacity at the heart rate threshold
*significant at $p < 0.05$ level

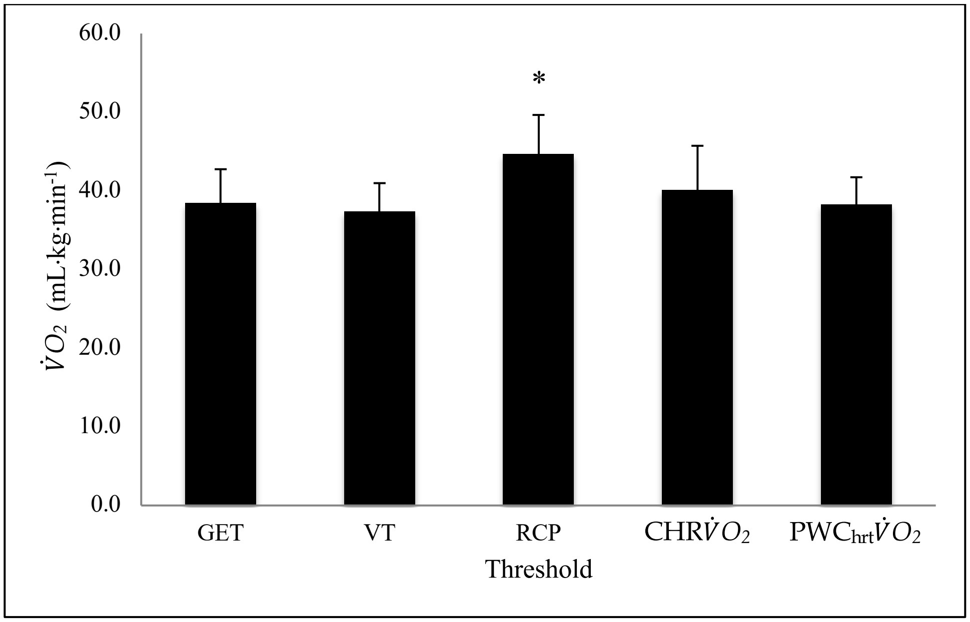

Figure 6. Visual representation of the mean ± SD for each of the thresholds determined from the incremental treadmill test and constant velocity runs. *significantly greater than GET, VT, and PWC$_{hrt}\dot{V}O_2$ ($p < 0.05$).

DISCUSSION

The purpose of this study was to compare the metabolic intensities corresponding to HR based fatigue thresholds to those derived from gas exchange and ventilatory parameters that define the moderate, heavy, and severe exercise intensity domains. The mean $\dot{V}O_{2peak}$ values for the subjects in the present study were considered "good" according to ACSM guidelines (37) classification for cardiorespiratory fitness and were consistent with the values for moderately trained individuals (Table 1). The GET (78% ± 7% of $\dot{V}O_{2peak}$) and VT (76 ± 4%$\dot{V}O_{2peak}$) were not different and reflected a similar, but slightly greater, relative intensity to previously reported values for these thresholds (GET = 66% ± 7%$\dot{V}O_{2peak}$; VT = 60% ± 8%$\dot{V}O_{2peak}$) in moderately trained subjects (4, 11, 15). Consistent with previous research (4), the RCP (90% ± 4%$\dot{V}O_{2peak}$) occurred at a higher intensity than the GET and VT in the present study (Table 1). Therefore, the current findings supported the results of previous studies (2, 4, 15) and indicated the GET and VT represented a similar threshold, while the RCP occurred at higher intensity and represented a different mechanism of fatigue.

The similarity in the GET and VT in the present study is consistent with previous research and is a reflection of the physiological mechanisms underlying these thresholds (2). Although there are some alternative hypotheses (24), it is generally suggested that the dissociation of $\dot{V}CO_2$ from $\dot{V}O_2$ at the GET reflects the excess carbon dioxide generated from the bicarbonate buffering of free hydrogen ions as a result of increased non-mitochondrial ATP hydrolysis (40). The increase in $\dot{V}_E$ relative to $\dot{V}O_2$ at the VT represents the corresponding increase in ventilation to eliminate the excess carbon dioxide (2). Thus, the GET and VT reflect the highest intensity that can be sustained with reliance primarily on aerobic ATP reconstitution and reflect the demarcation of the moderate from the heavy exercise intensity domains. The non-linear increase in $\dot{V}_E$ relative to $\dot{V}CO_2$ at the RCP, however, reflects the ventilatory response to the failure of the bicarbonate buffering system (2) and/or hyperkalemia (14), and has been suggested to provide an estimate of the demarcation of the heavy from the severe exercise intensity domains (2, 4).

In the current study, the CHR$\dot{V}O_2$ was not different from the GET, VT, or RCP, which indicated the initial metabolic intensity at the CHR was likely within the heavy domain. The CHR has previously been reported (32) to be significantly greater than the HR corresponding to the VT (92.9 ± 2.7 %HR_{max} vs 82.1 ± 4.3 %HR_{max}, respectively), and similar to the HR at the RCP (92.9 ± 2.7 %HR_{max} vs 92.9 ± 2.2%HR_{max}). In contrast, the $PWC_{hrt}\dot{V}O_2$ was not different from the GET and VT in the present study, but was significantly lower than the RCP, which indicated the initial metabolic intensity at the PWC_{hrt} was likely within the moderate intensity domain. These findings were consistent with previous work that has shown the power output at the PWC_{hrt} (64 ± 8% max power output) to be equal to the power output at the VT (61 ± 11% max power output) and located within the moderate intensity domain (30). Other researchers have used the same mathematical modeling used to derive the PWC_{hrt} to derive fatigue thresholds for other physiological and perceptual variables such as muscle activation [EMG_{FT} (54 ± 10% max power output)], perception of effort [PWC_{BORG} (63 ± 7% max power output)] and [PWC_{OMNI} (64 ± 9% max power output)], and metabolic rate [PWC_{VO2} (69 ± 7% max power output)] and have found no difference between the power outputs associated with each threshold and the VT (11, 30, 33). One limitation within the current literature is that previous studies have examined only the HR or power output associated with each threshold and have not looked at the metabolic intensities (3, 18, 28, 31, 33, 44, 45), which are used to define the exercise intensity domains. Overall, the current findings showed the CHR$\dot{V}O_2$ represented an initial metabolic intensity that was within the heavy domain and was lower than the estimated initial intensity previously reported (32) for comparisons based on HR or power output. Additionally, the $PWC_{hrt}\dot{V}O_2$ represented a similar initial metabolic intensity as previously reported (equal to the VT and GET) and was likely located within the moderate intensity domain.

The CHR and PWC_{hrt} have a number of applications for prescribing cardiorespiratory endurance exercise as they provide insight into individual submaximal performance capabilities (5, 6, 32). The $PWC_{hrt}\dot{V}O_2$ provides the initial metabolic intensity of the exercise, but exercise prescription at the PWC_{hrt} is based on a velocity. During constant velocity exercise within the moderate domain, there are increases in HR and $\dot{V}O_2$ at the onset of exercise that quickly stabilize without an increase in blood lactate concentration (21). Moderate exercise intensities maintained for 10-20 minutes are also associated with a cardiovascular drift (~11% increase in HR over time) and changes in $\dot{V}O_2$ of less than 150 ml·min^{-1} (12). The PWC_{hrt} has been shown (44) to be sustainable for 60 mins with a HR increase of 0.066 bpm·min^{-1}, which reflects a rate of rise that is less than the cardiovascular drift response for moderate exercise intensities. From an exercise prescription perspective, the PWC_{hrt} may be an appropriate intensity for previously untrained or sedentary individuals during the initial phase of the program. However, in trained populations, the physiological responses associated with the PWC_{hrt} may not be high enough to provide the overload stimulus required to elicit cardiorespiratory adaptations (22, 29, 38). For both populations, a training session at the PWC_{hrt} represents a similar intensity to the easy pace as identified by Daniels (1989). Conversely, the CHR is a HR based intensity, and in the present study, reflected a metabolic intensity consistent with the heavy domain that typically can be maintained for less than 60 min (5). When exercise is anchored by a physiological parameter, such as HR, there are dissociations in physiological variables (i.e., $\dot{V}O_2$, HR, breathing frequency, minute ventilation) that are typically associated with, and demonstrate predictable time-dependent increases during constant velocity or power output exercise (8, 9, 14, 16, 21, 23, 36). Specifically, constant HR exercise requires a gradual decrease in velocity (or power output) (-23 ± 6%) to maintain HR (5). Consequently, other parameters, such as $\dot{V}O_2$ decrease along with the decreasing workload (-16 ± 8%) (5). For endurance-trained individuals, exercise intensities above the GET or VT (78% and 76%$\dot{V}O_{2peak}$, respectively) are recommended to elicit adaptations. Therefore, exercise at CHR (81%$\dot{V}O_{2peak}$) would begin at a metabolic intensity within the heavy intensity domain, but may drift into the moderate intensity domain if sustained for greater than 30 min. This would reflect tempo/threshold training as part of a comprehensive cardiorespiratory training program (13, 25). Thus, the PWC_{hrt} (upper end of the moderate domain) may provide a relative intensity that is more appropriate for untrained populations for a long/easy pace, while the CHR (middle to higher end of the heavy domain) may be an appropriate intensity for trained populations for the marathon and threshold paces.

One of the primary advantages of using the PWC_{hrt} and CHR to prescribe training intensities is that they are based on individual performance capabilities, rather than a percentage of $\dot{V}O_{2max}$, and they are derived from a physiological (HR) measure. Therefore, these thresholds allow athletes to select exercise intensities within a given domain (moderate, heavy, and severe) without the need for a metabolic cart and the measurement of gas exchange parameters to calculate the GET, VT, and RCP. The calculation of the PWC_{hrt} and CHR require the use of only a treadmill, a stopwatch, and the measurement of HR. The current findings indicated the PWC_{hrt} and CHR reflected intensities within the moderate and heavy domains, respectively, which provide utility for varying fitness levels and training session goals. Untrained populations starting a cardiorespiratory endurance training program, or trained populations aiming for a long/easy pace session may use the PWC_{hrt} to identify the target intensity, while trained populations may use the CHR for a marathon/threshold training pace. Thus, the PWC_{hrt} and CHR may allow for the development of an individualized cardiorespiratory endurance training program without the need for expensive laboratory equipment. Future studies should examine the adaptations from an individualized cardiorespiratory endurance training program that is based on the PWC_{hrt} and CHR compared to the adaptations from a program using the traditional intensities prescribed at a percentage of maximal heart rate (HR) or $\dot{V}O_{2max}$.

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