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Original Research

Mathematical Modeling and Expression of Heart Rate Deflection Point using Heart Rate and Oxygen Consumption

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ABSTRACT

International Journal of Exercise Science 10(4): 592-603, 2017. Heart rate deflection point (HRDP) can be determined through different mathematical-modeling procedures, such as bi-segmental linear regression (2SEG) or maximal distance model (Dmax). The purpose was to compare heart rate (HR) and oxygen consumption (VO_2) at HRDP when using 2SEG and Dmax, and to examine their relationships with respiratory compensation point (RCP) and running performance. Nineteen participants completed a graded exercise test (GXT), to determine HRDP and RCP, and a 5km treadmill time trial ($5K_{time}$). No differences were found in HR or VO_2 when comparing $HRDP_{2SEG}$, $HRDP_{Dmax}$, and RCP. Strong correlations were found between $HRDP_{2SEG}$, $HRDP_{Dmax}$, and RCP when using HR and VO_2. No relationships were found between $5K_{time}$ and HR at HRDP or RCP; however, strong relationships were found with VO2. While 2SEG and Dmax may be interchangeable in determining HRDP, VO_2 at HRDP and RCP yielded stronger relationships to $5K_{time}$ than HR. Therefore, VO_2 at HRDP may be a better predictor of running performance than HR.

KEY WORDS: Anaerobic threshold, Dmax, maximal distance method, bi-segmental linear regression, respiratory compensation point

INTRODUCTION

The anaerobic threshold, considered to be the point at which blood lactate production begins to increase beyond the rate of its removal, is highly correlated to endurance performance and is often used to determine an athlete's training intensity (4, 5, 19, 23). During a graded exercise test (GXT), heart rate (HR) and exercise intensity will theoretically increase at a linear rate. However, HR will depart from the linearity of the HR versus speed or time relationship at different intensities, which have been identified as specific breakpoints (3). The breakpoints in the HR versus speed or time relationship may be useful when designing training programs, specifically through the use of exercise intensity domains (6, 14).

Optimal training intensities vary between individuals and training goals. Researchers have investigated and defined four main exercise intensity domains, including those reflective of moderate, heavy, severe, and extreme intensities (16, 34). These breakpoints occur when HR departs from linearity in the HR versus speed or time relationship curve. The first breakpoint in this relationship has been shown to be indicative of the aerobic threshold (1), signifying the transition from moderate to heavy exercise intensity and is often associated with the "first lactate turn point" (9) or the ventilatory threshold (VT) (25). The second breakpoint in linearity, termed heart rate deflection point (HRDP) (2, 7, 9, 23, 32), has been shown to be indicative of the anaerobic threshold signifying the transition from heavy to severe exercise intensity and is often associated with the "second lactate turn point" (1, 9) or the respiratory compensation point (RCP) (25).

There is no standardized method to identify the breakpoint in HR linearity; therefore, researchers have utilized different approaches to identify HRDP, with some of the most common methods being bi-segmental linear regression (2SEG) and the maximum distance model (Dmax). 2SEG has been shown to provide strong correlations between HRDP and performance measures, such as time and duration, and metabolic thresholds (15, 17). For example, Grazzi et al. (15) found that HRDP strongly correlated with anaerobic (ventilatory) threshold when both were determined via 2SEG. Similarly, Dmax has been shown to provide accurate estimates of HRDP (13, 23, 30) and strong relationships with outdoor running performance time (8, 27). However, a direct comparison of 2SEG and Dmax has yet to be conducted. Further, the physiological variable, such as HR or VO_2, used to express HRDP has been inconsistently reported, which may lead to discrepancies with regard to performance measures (4, 15, 23, 25, 30). Therefore, the purposes of the current study were to examine the relationship and differences between HRDP when determined with different mathematical models (2SEG versus Dmax) and expressed as different physiological variables (HR and VO_2), and to examine the relationships between HR and VO_2 at HRDP, HR and VO_2 at RCP and 5-km time trial performance. It was hypothesized that no significant differences would be present between mathematical models to determine HRDP and that HRDP would be related to RCP and 5-km time trial performance.

METHODS

Participants

Twenty-three recreationally active individuals between the ages of 18 and 35 were recruited for this study (men, n = 10; women, n = 13). Two female participants were removed due to non-study related health reasons, and one for failure to comply with the testing protocol. One male participant was removed due to inability to determine HRDP. Therefore, data for 9 males (age 25.56 ± 3.17 years; height 1.77 ± 0.05 meters; body mass 83.52 ± 6.77 kilograms) and 10 females (age 22.78 ± 2.11 years; height 1.64 ± 0.07 meters; body mass 62.28 ± 6.20 kilograms) were included in the final analysis. All participants were required to exercise a minimum of three days per week to be considered recreationally active.

Protocol
On the initial visit, anthropometrics were collected and participants were familiarized with the testing protocol. On the first testing day, participants performed a (GXT) on a treadmill to determine HRDP and estimate VO_2peak. On the second testing day, participants completed a 5-km time trial on a treadmill. The testing days were separated by a minimum of 48 hours, and participants were asked to arrive at the same time of day for each testing session. All testing was completed in a temperature and humidity controlled laboratory. Participants were required to arrive two hours post-prandial and to abstain from exercise for at least 24 hours prior to each testing session. In addition, each participant was asked to replicate their dietary habits, assessed via dietary food logs completed for the day before and day of each trial, and to refrain from consuming caffeine on the day of the trial.

Informed consent was obtained from each participant following an explanation of the study's procedures. The Institutional Review Board approved the research protocol. Through completion of a Physical Activity Readiness Questionnaire (PAR-Q) and medical history questionnaire, it was determined that no participants had any history of cardiovascular, metabolic, renal, hepatic, or musculoskeletal disorders or were taking any medications.

The GXT was completed on a motorized treadmill (Woodway Desmo™, Waukesha, Wisconsin, United States). Participants completed a five-minute warm-up on the treadmill at a self-selected speed prior to testing. Each participant was fitted with a HR monitor (Polar® RS800CX, Kempele, Finland), and body mass was measured on a calibrated physician's scale (Patient Weighing Scale, Model 500 KL, Pelstar, Alsip, IL, USA). The GXT protocol was individualized and based on a modification of the Bruce protocol (22). Subjects completed a two-minute warm-up phase, which was excluded from data analysis. Immediately after the two-minute warm-up, the first stage of the test began at a speed equivalent to the participant's estimated one-mile running time. Treadmill speed was increased by 1.6 kilometers per hour (km/hr) every two minutes, for six minutes. For the remainder of the test, treadmill incline (or grade) increased by 1.0% every 60 seconds with no change in speed until the participant could no longer continue. During this test, participants' HRs were recorded and respiratory measures were collected using a metabolic cart. Participants were not able to see their speed, distance, or time during the treadmill test in order to decrease bias related to motivation between exercise tests.

Prior to the GXT, the metabolic cart (True One 2400® Metabolic Measurement System, Parvo Medics, Inc., Sandy, Utah, United States) and flowmeter were calibrated (24). Participants were set up with a breathing apparatus in order to analyze respiratory gases, as demonstrated by previous research in our laboratory (24). VO_2peak criteria was set forth by Howley et al. (18). All participants included in data analysis obtained a VO_2peak of 35 $ml \cdot kg^{-1} \cdot min^{-1}$ or greater.

HRDP values were determined using two methods: (1) Dmax method utilizing an exponential-plus-constant regression model ($HRDP_{Dmax}$, Figure 1a) and (2) bi-segmental linear regression ($HRDP_{2SEG}$, Figure 1b). For each method, HR values were analyzed using a cutoff point starting at 80% of the participants' maximum achieved HR during the GXT.

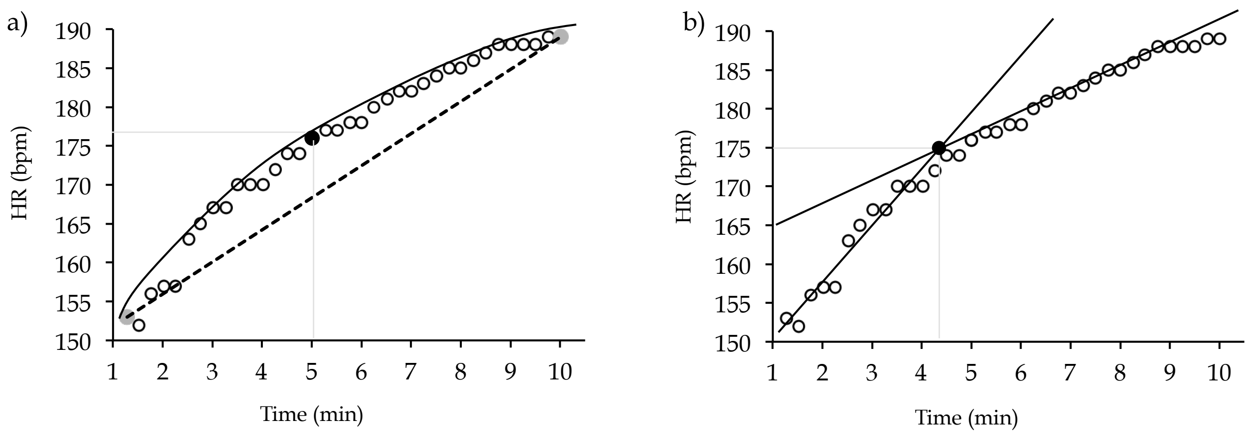

Figure 1. Single participant's HRDP (closed marker) determined via (a) Dmax method and (b) 2SEG method.

$HRDP_{Dmax}$ was considered to be the point at which the slope of the exponential plus constant regression curve was equal to the slope of the linear regression line connecting the first and last HR points. Alternatively, this deflection point denotes the maximum perpendicular distance between the linear and nonlinear regression lines. The exponential-plus-constant model was used to determine HRDP from HR and time (t), using the following equation (8):

$$HR(t) = a + (b \times e^{c \times t})$$

The coefficients a, b, and c, as well as the coefficient of determination (r^2), were calculated through use of a computerized graphing program (Origin, OriginLab Corporation, Northampton, Massachusetts). The following formula was then used to determine the HRDP in Microsoft Excel:

$$HRDP = \frac{\ln\left(\frac{\left(\left(e^{(c*\max t)}\right) - \left(e^{(c*\min t)}\right)\right)}{\left((c*\max t) - (c*\min t)\right)}\right)}{c}$$

In order to find $HRDP_{2SEG}$, the HR versus time curve was divided into two linear regression segments, with HRDP denoting the intersection of the two segments. A computerized data analysis and graphing program (Origin, OriginLab Corporation, Northampton, Massachusetts) was used for this method. A piecewise fitting function was defined consisting of two linear segments, expressed as (11):

$$Y = \begin{cases} \dfrac{y1(x3-x)+y3(x-x1)}{x3-x1}, & \text{if } x < x3 \\ \dfrac{y3(x2-x)+y2(x-x3)}{x2-x3}, & \text{if } x \geq x3 \end{cases}.$$

After fitting the data, $HRDP_{2SEG}$ were calculated by defining the bisection of the two linear segments from the fitting result. For both $HRDP_{Dmax}$ and $HRDP_{2SEG}$, HR and VO_2 values were used to express HRDP.

RCP values were also determined via 2SEG and were analyzed using the previously described cutoff point. However, instead of the HR versus time curve, a VE versus VCO_2 curve was used to determine RCP from the intersection of two linear regression lines. RCP was also expressed as HR and VO_2.

For the treadmill time trial, each participant was fitted with a HR monitor (Polar® RS800CX, Kempele, Finland) to record HR, and body weight was measured on a calibrated physician's scale (Patient Weighing Scale, Model 500 KL, Pelstar, Alsip, IL, USA). Participants performed a 5-minute warm-up at a self-selected intensity on a motorized treadmill (Woodway Desmo™, Waukesha, Wisconsin, United States). Participants were not able to see their speed or time during the treadmill time trial but were able to monitor their distance. Total time to completion ($5K_{time}$) was recorded.

Statistical Analysis

All data were analyzed to provide descriptive statistics for $HRDP_{2SEG}$, $HRDP_{Dmax}$, RCP, and $5K_{time}$. Statistical analysis was conducted through use of SPSS (Version 21.0). One-way repeated measures analysis of variance (ANOVA) was used to compare HR and VO_2 values at $HRDP_{2SEG}$, $HRDP_{Dmax}$, and RCP. Effect size was also reported for each ANOVA ($\square^2$). Pearson product moment correlations were used to examine the relationship between the HRDP estimation methods and both RCP and $5K_{time}$ performance. Pearson's r was considered strong when values were between 0.70 and 1.00, moderate when values were between 0.45 and 0.70, and weak when values were between 0.20 and 0.45 (12). Bland Altman plots were created to evaluate the levels of agreement between $HRDP_{2SEG}$, $HRDP_{Dmax}$, and RCP. Systematic bias was identified as a significant slope in the relationship between the average and mean difference values for the variables of interest. An alpha level of $p \leq 0.05$ was used to determine statistical significance.

RESULTS

The VO_2peak values from the GXT were 48.98 ± 7.37 $ml \cdot kg \cdot min^{-1}$ for men and 42.32 ± 4.13 $ml \cdot kg \cdot min^{-1}$ for women, while the $5K_{time}$ was 26.82±3.15 min for men and 30.61±4.51 min for women. Individual and mean (± 95% confidence interval) $HRDP_{2SEG}$, $HRDP_{Dmax}$, and RCP values using HR and VO_2 are shown in Figure 2a and Figure 2b, respectively. Values (mean ± standard deviation) for VO_2 at $HRDP_{Dmax}$ and $HRDP_{2SEG}$ as a percent of VO_2peak were 83.86 ± 4.45% and 81.61 ± 6.93%, respectively, and values for HR at $HRDP_{Dmax}$ and $HRDP_{2SEG}$ as a percent of maximum HR (%HRmax) were 92.26 ± 1.20% and 91.48 ± 3.10%, respectively. No significant differences were found between HR at $HRDP_{2SEG}$, HR at $HRDP_{Dmax}$, and HR at RCP ($F_{2,36} = 3.739$, $p = 0.533$, $\square^2 = 0.034$) or between VO_2 at $HRDP_{2SEG}$, VO_2 at $HRDP_{Dmax}$, and VO_2 at RCP ($F_{2,36} = 1.163$, $p = 0.324$, $\square^2 = 0.061$). Because no difference was seen between Dmax and 2SEG methods for HRDP, only $HRDP_{Dmax}$ was reported for relationship with RCP and $5K_{time}$.

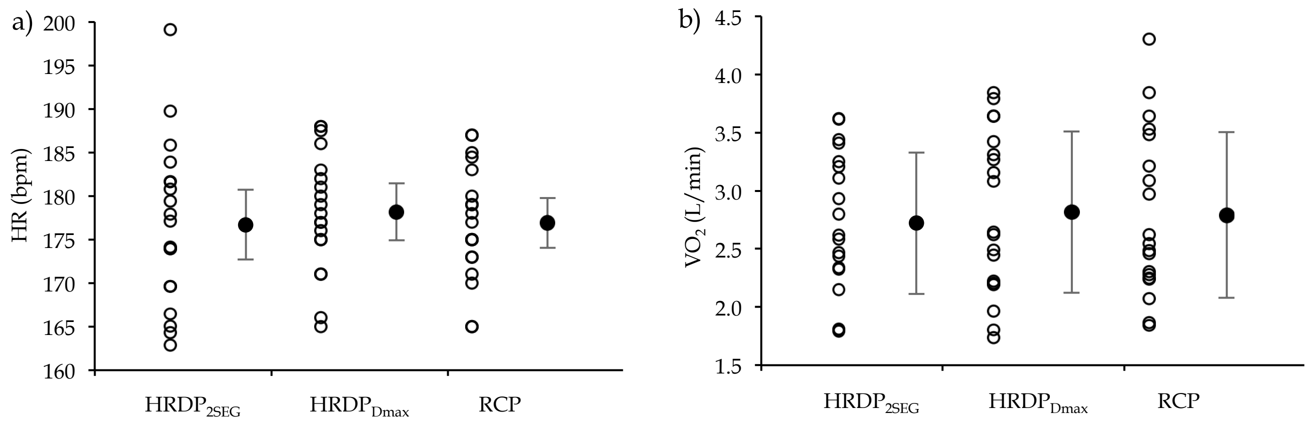

Figure 2. Individual values (open circles) and mean (±95% confidence interval) values (closed circles) for a) HR and b) VO_2 at $HRDP_{2SEG}$, $HRDP_{Dmax}$, and RCP.

When comparing VO_2 at $HRDP_{Dmax}$ to VO_2 at RCP, a strong positive correlation was shown (r = 0.926, $p < 0.0001$, Figure 3a), Bland-Altman plots and limits of agreement are shown in Figure 3b. Similar limits of agreement were found for VO_2 at $HRDP_{Dmax}$ and VO_2 at RCP, with the differences of the mean values lying within ±95% confidence intervals. A non-significant slope was found, indicating no proportional bias (p = 0.818). Furthermore, moderate correlations were found between VO_2 at $HRDP_{Dmax}$ and $5K_{time}$ (r = -0.569, p = 0.011, Figure 4a), and VO_2 at RCP and $5K_{time}$ (r = -0.650, p = 0.003, Figure 4b).

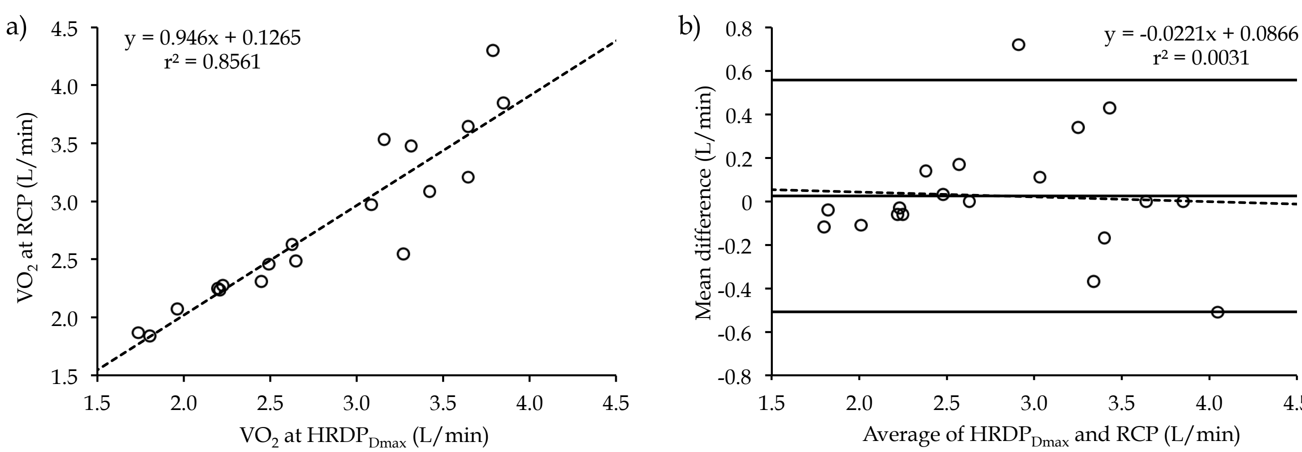

Figure 3. Relationship between a) VO_2 at HRDP and VO_2 at RCP and b) corresponding Bland-Altman plot.

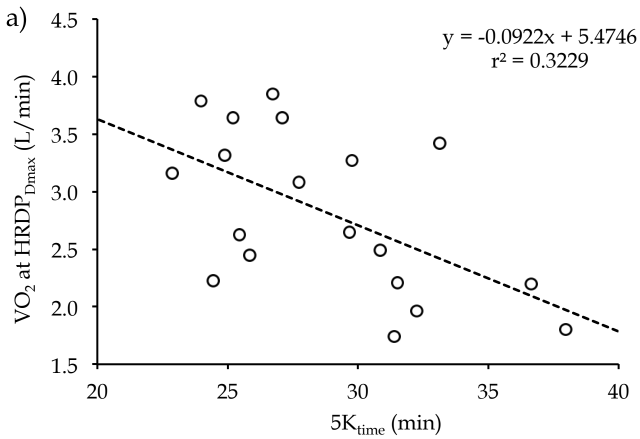

Figure 4. Relationship between $5K_{time}$ and a) VO_2 at HRDP and b) VO_2 at RCP.

When comparing HR at $HRDP_{Dmax}$ to HR at RCP, a moderate positive correlation was shown ($r = 0.619$, $p = 0.005$, Figure 5a). Bland-Altman plots and limits of agreement are shown in Figure 5b. Similar limits of agreement were found for HR at $HRDP_{Dmax}$ and HR at RCP, with the differences of the mean values lying within ±95% confidence intervals. A non-significant slope was found, indicating no proportional bias ($p = 0.868$). Furthermore, non-significant weak correlations were found between HR at $HRDP_{Dmax}$ and $5K_{time}$ ($r = 0.241$, $p = 0.321$, Figure 6a), and HR at RCP and $5K_{time}$ ($r = 0.193$, $p = 0.429$, Figure 6b).

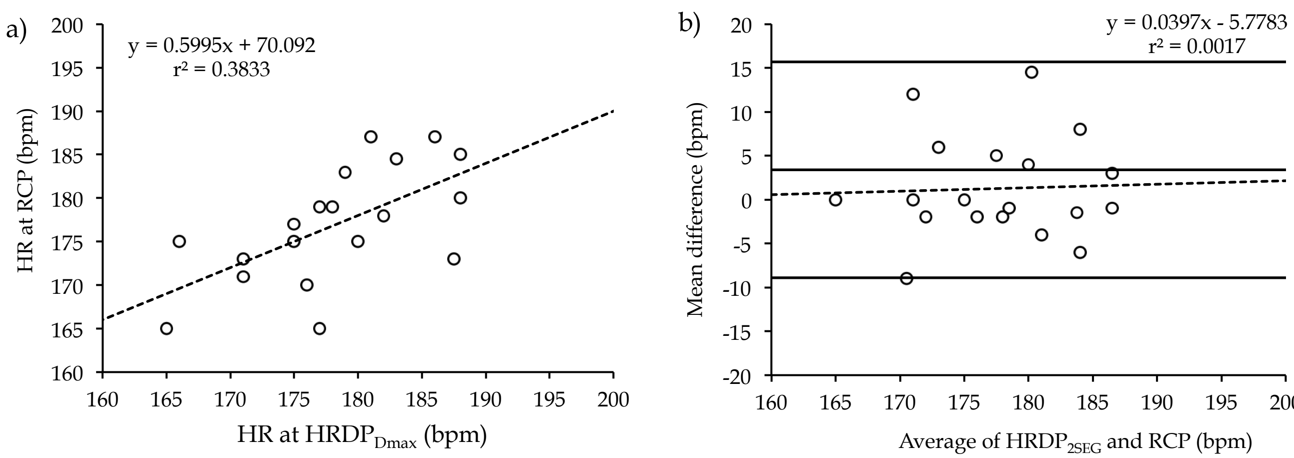

Figure 5. Relationship between a) HR at HRDP and HR at RCP and b) corresponding Bland-Altman plot.

DISCUSSION

This study aimed to examine the relationship between different HRDP estimates and a potentially corresponding performance measure ($5K_{time}$), as well as a metabolic threshold determined using gas exchange analysis (RCP). While all of the examined methods (2SEG, Dmax, HR, VO_2) used to determine HRDP, as well as RCP, provided similar estimates of anaerobic threshold, using HR to express these thresholds was not indicative of 5,000m treadmill running performance. Interestingly, VO_2 values at HRDP and RCP were both positively correlated with $5K_{time}$, which demonstrates a potential dissociation between HR and VO_2 estimates of these thresholds with this measure of performance.

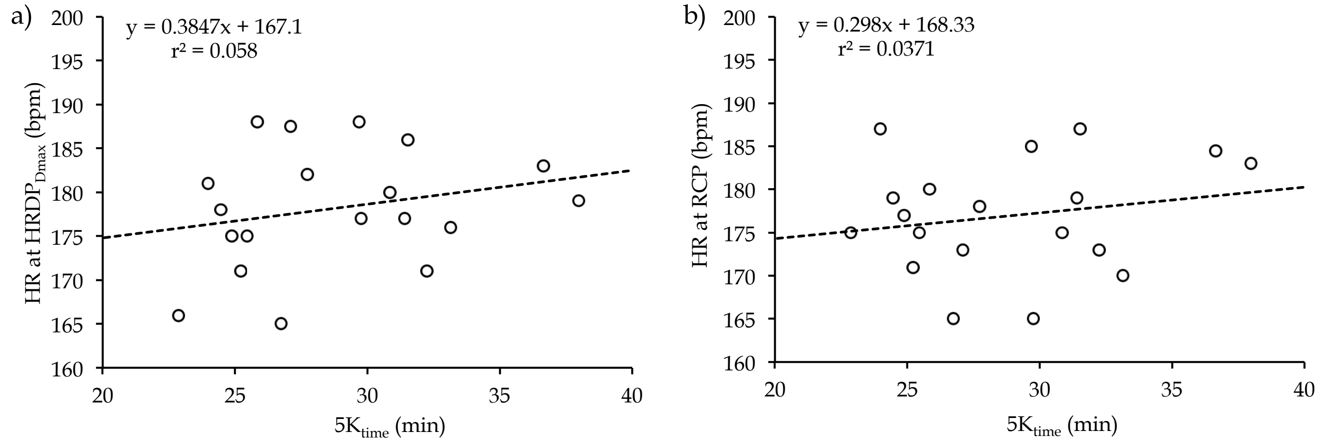

Figure 6. Relationship between $5K_{time}$ and a) HR at HRDP and b) HR at RCP.

Previous research has independently established Dmax and 2SEG to be valid methods of non-invasively determining HRDP to estimate performance variables when compared to a more invasive measure of obtaining blood lactate levels (17, 27). In a study conducted by Pereira et al. (27), researchers investigated the relationship between $HRDP_{Dmax}$ and maximal lactate steady state in active college-aged males. Following a 3,000m time trial on a 400m track to establish mean running velocity, subjects performed a GXT on a motorized treadmill. These researchers found no significant difference between velocity at the $HRDP_{Dmax}$ and the velocity at maximal lactate steady state ($p > 0.05$) (27), demonstrating that the Dmax method of determining HRDP may be an accurate measure to estimate running velocity at maximal lactate steady state. The Dmax method used in the current investigation was based on a study conducted by Da Silva, Peserico, & Machado in middle-aged recreationally-active women who found that using an exponential-plus-constant regression curve model provided a higher correlation between $HRDP_{Dmax}$ and 10,000m running performance ($r = 0.96$) than a third-order polynomial regression curve model (8).

In addition to using Dmax to determine HRDP, researchers have also examined the 2SEG method and its accuracy for estimating anaerobic threshold. Higa et al. (14) found a strong relationship between $HRDP_{2SEG}$ and (ventilatory) anaerobic threshold determined from 2SEG ($r = 0.75$, $p < 0.05$) in recreationally active females in the same age range as those in the current study, as well as a group of recreationally active older females. These results, in combination with others, support the use of 2SEG as an acceptable method of determining HRDP (1, 4, 5, 9, 23). To the best of the authors' knowledge, the direct comparison of the Dmax and 2SEG methods of estimating HRDP in the current study support is unique and, due to the similar and related values, provides support for the use of either approach in recreationally-trained men and women.

No previous research has directly compared the use of HR and VO_2 to express HRDP; however, the training statuses of the individuals being tested may play a role in the value of these measures with regard to performance. Specifically, peak VO_2 may be improved through aerobic training, while maximal HR remains relatively stable (35). The potential for divergent adaptions in these physiological variables to maximal exercise likely affect the identification of fatigue thresholds, including HRDP. In support, the range of HR values at HRDP in the current study were relatively small (165-188 bpm; 90.00-94.40% of HRmax) compared to the range of VO_2 values at HRDP (1.74-3.85 L/min; 74.60-91.46% of VO_2peak). Furthermore, differences in the HR-VO_2 relationship according to training status have been established, with a steeper slope exhibited in recreational versus endurance-trained individuals (29). Thus, for a given HR, trained individuals exhibit greater VO_2 values than untrained individuals. The relatively untrained nature of the current sample and HR at HDRP values of approximately 92.6% of maximum may have resulted in a dissociation with VO_2 at HRDP and influenced the relationship between these variables and $5K_{time}$.

The utility of specific fatigue threshold variables, such as HR versus VO_2, as indicators of performance may be limited by the duration of the activity of interest (28, 32). Tokmakidis and Leger demonstrated a lack of relationship to shorter distance running performance ($r = 0.235$, $p > 0.05$, distance = 500m; $r = 0.098$, $p > 0.05$, distance = 300m) when expressing HR as HRDP (33). More relevant to the current investigation with regard to duration, Dumke et al. (10) reported significant correlations ($r = 0.71$ to 0.78) between a 60-minute cycling time trial and HR at a variety of lactate thresholds (corresponding to ~90% of HRmax) that were not apparent when compared to 30-minute time trial performance. Strong correlations have been shown to exist between long-distance cycling performance and VO_2 at second ventilatory threshold ($r = -0.75$, $p < 0.001$, mean duration = 66 minutes) and RCP ($r = -0.66$, $p < 0.05$, mean duration = 113.77 minutes) (20, 31). RCP, expressed as VO_2, is also related ($r > 0.70$) to shorter distance (~5000m; < 20 minutes) running performance (21, 26). These findings indicate that when relating fatigue thresholds to athletic performance, expression as HR values should be used with caution while VO_2 may be preferred.

No differences were seen between Dmax and 2SEG or between HRDP and RCP, signifying that the method used to determine either of these estimates of anaerobic threshold may not be as important as the physiological variable chosen to express them. While limited to the results of this study, VO_2 may be a more appropriate expression of HRDP or RCP compared to HR when relating to 5K running time in recreationally-active adults. However, multiple factors should be taken into consideration when indirectly estimating anaerobic threshold for performance, such as the GXT protocol, training statuses of the participants, and distance of the time trial. Furthermore, the current study utilized a particularly heterogeneous group of volunteers, and examination of the relationship between HRDP, utilizing both HR and VO_2, and running performance is needed in more homogeneous samples.

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