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RESPONSES TO EXERCISE ANCHORED TO VIGOROUS INTENSITY HEART RATES

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RESPONSES TO EXERCISE ANCHORED TO VIGOROUS INTENSITY HEART RATES

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in the
College of Education
at the University of Kentucky

By

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2023

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ABSTRACT OF THESIS

RESPONSES TO EXERCISE ANCHORED TO VIGOROUS INTENSITY HEART RATES

Exercise prescription to improve cardiorespiratory endurance (CE) is often based on percentages of the reserve or maximum heart rate (HR_{peak}) or oxygen consumption rate ($\dot{V}O_{2peak}$) that reflect vigorous intensities (77-95% HR_{peak}, 64-90% $\dot{V}O_{2peak}$). These intensities elicit a rating of perceived exertion [RPE] response between 14-17 on the 6-20 Borg Scale. It is recommended that exercise within these ranges be sustained for 20-60min per session. The purposes of this study were to: 1) Determine the metabolic ($\dot{V}O_2$) and perceptual (RPE) responses as well as the sustainability of exercise (time to exhaustion [T_{lim}]) anchored to heart rates (HR) at the lower (HR_L= 77% peak heart rate [HR_{peak}]), middle (HR_M=86% HR_{peak}), and higher (HR_H= 95%HR_{peak}) ends of the range recommended for vigorous exercise; 2) determine if the $\dot{V}O_2$ and RPE response remain within the recommended ranges for vigorous exercise throughout the trials at HR_L, HR_M, HR_H by examining the time course of changes and patterns of responses for these variables as well as power output (PO), respiratory exchange ratio (RER), minute ventilation ($\dot{V}_E$), and respiratory rate (RR) responses; and 3) determine the time spent in the severe (> respiratory compensation point [RCP]), heavy (< RCP, > ventilatory threshold [VT]), and moderate (< VT) intensity domains for the composite and on a participant-by-participant basis during each of the constant HR trials. Twelve, moderately trained, participants performed a graded exercise test to exhaustion on a calibrated cycle ergometer to determine the peak responses for HR (HR_{peak}), $\dot{V}O_2$ ($\dot{V}O_{2peak}$), RPE, RER, $\dot{V}_E$, RR, and peak power output as well as the VT and RCP. On separate days, constant HR trials were performed at HR_L, HR_M, and HR_H, in a randomized order. The $\dot{V}O_2$, RER, $\dot{V}_E$, RR, power output (PO), RPE, and T_{lim} were examined during the randomly ordered continuous trials to exhaustion or up to 60 min. The HR_L (143±8 beats·min^{-1} [b·min^{-1}]), the HR_M (159±8 b·min^{-1}), and the HR_H (176±9 b·min^{-1}) were maintained for 53.42±13.19, 46.75±18.79, and 27.05±18.00 min, respectively, not including the time to reach the desired HR. A one-way repeated measures ANOVA (F=26.196, $p \leq 0.001$, η_p^2=0.704) and post-hoc, t-tests with a Bonferroni corrected alpha ($p < 0.017$) indicated the T_{lim} at HR_L and HR_M were both

significantly longer than T_{lim} at HR_H ($p < 0.001$), but T_{lim} for HR_M and HR_L were not different. Responses across time were examined with 3(Intensity: HR_L, HR_M, and HR_H) x 10(Time: 10-100%Tlim) repeated measures ANOVAs and post-hoc analysis. The $\dot{V}O_2$, collapsed across intensity, was significantly lower than the initial value (10%T_{lim}) from 20-100% T_{lim} ($p < 0.001$). The RPE, collapsed across intensity, was significantly higher than the initial value (10%) from 30-100% of T_{lim} (p=0.0001 to 0.0019). For HRL trial, the composite (average of all subjects across time) $\dot{V}O_2$ (53.9±7.1% $\dot{V}O_{2peak}$) and RPE (RPE of 12±3) responses were lower than the recommended range during the trials. For the HR_M trial, the average $\dot{V}O_2$ (64±7% $\dot{V}O_{2peak}$) and RPE (RPE of 14±2) responses were within the recommended range for 40% (~19 min) and 70% of T_{lim}, respectively. For HR_H trial, the average $\dot{V}O_2$ (80±8% $\dot{V}O_{2peak}$) and RPE (RPE of 17±1) responses were within the recommended range for the entire trial. On a participant-by-participant basis, the HR_H was the only intensity where approximately half of the participants were within the recommended $\dot{V}O_2$ (58% of participants) or RPE (67% of participants) ranges for 20 min. An additional 3(Intensity: HR_L, HR_M, and HR_H) x 10(Time: 10-100%Tlim) repeated measures ANOVAs and post-hoc analysis were performed for PO, RER, $\dot{V}_E$, and RR. The PO, collapsed across intensity, was significantly lower than the initial value (10%) from 20-100% of T_{lim} (p=0.0002 to 0.0014) for all comparisons. The RER at HR_L, HR_M, and HR_L, were significantly lower than the initial value (10%) from 20-100% of T_{lim} (p=0.0001 to 0.0006). The RER for HR_H was greater than HR_L and HR_M at most time points, however, there were no differences in RER between HR_L and HR_M. The $\dot{V}_E$, collapsed across intensity, was significantly lower than the initial value (10%) from 20-100% of T_{lim} (p=0.0001 to 0.0002) and the RR, collapsed across intensity, was significantly higher than the initial value (10%) from 70-90% of T_{lim} (p=0.0013 to 0.0019). The repeated measures ANOVA examining time in each intensity domain indicated there was a 2-way interaction (F =25.588, $p \leq 0.001$, η_p^2 =0.699). The post-hoc t-tests indicated that at HR_L, the participants spent significantly more in the moderate domain than the heavy ($p \leq 0.001$) and severe ($p \leq 0.001$). There was no significant difference in the time spent within the heavy and severe domains (p=0.053). At HR_M, more time was spent in the moderate than the heavy (p=0.002) and severe ($p \leq 0.001$) domains and there was more time spent within the heavy than the severe (p=0.010). Finally, at HR_H there were no significant differences between the time spent in the moderate compared to the heavy domain (p=0.318), severe (p=0.017), or between the heavy and severe (p=0.036). There were intensity specific metabolic demands that demonstrated the HR_H elicited the highest metabolic cost and RER relative to HR_M and HR_L. The decreases in $\dot{V}O_2$ tracked PO and $\dot{V}_E$ followed a similar pattern for each trial. The RPE increased during each HR trial and RR tracked this response. The increases in RPE may be attributed to an increase in the RR and feedback from mechanical and metabo-sensitive group III/IV afferent neurons. The $\dot{V}O_2$ and RPE findings indicated that exercise anchored at HR_L and HR_M may not provide an intensity that meets the current guidelines for improving CE fitness. While HR_H may be at a sufficient intensity to elicit the desired metabolic responses on average, it may not be for all participants. Thus, these data indicated that HR_{peak} should not be used to prescribe a desired metabolic intensity.

KEYWORDS: Cardiorespiratory Fitness, Vigorous Intensity, Perception of Effort, Cycling, Endurance Training, Metabolic Intensity

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DEDICATION

To God I dedicate this thesis for His amazing grace, He has been the source of my strength throughout this project.

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CHAPTER 1. INTRODUCTION

The current guidelines from the American College of Sports Medicine (ACSM) recommend that exercise prescriptions to improve cardiorespiratory endurance (CE) are based on percentages of the maximum rate of oxygen consumption ($\dot{V}O_{2max}$) or the reserve volume of oxygen consumption ($\dot{V}O_{2peak}$)(for consistency, the term peak will be used throughout this document). Heart rate (HR_{peak}) or the corresponding ratings of perceived exertion (RPE) are also commonly used when prescribing exercise (ACSM Guidelines, Garber et al. 2011). These recommendations include a range of moderate (64-76% HR_{peak}, 46-63 % $\dot{V}O_{2peak}$) or vigorous (77-95% HR_{peak}, 64-90% $\dot{V}O_{2peak}$) exercise intensities that are performed most days of the week at an intensity low enough to be sustained for 20 to 60 min, but high enough to elicit metabolic and cardiovascular adaptations (ACSM guidelines, Garber et al. 2011). The specific intensity required to improve cardiorespiratory fitness (CRF) is dependent upon the current training status of the individual, where moderate intensities may be appropriate for deconditioned or previously sedentary individuals, while vigorous to maximal/near maximal intensities (>91% $\dot{V}O_{2peak}$; > 96 HR_{peak}) may be required for more highly trained individuals (Garber et al.2011, Sisson et al.2009). Furthermore, the current recommendations suggest that intensity is determined relative to an individual's maximum or reserve capacity. These intensity ranges do not consider submaximal performance capabilities defined by an individual's fatigue threshold (e.g., lactate threshold) or the exercise intensity domain in which the exercise was prescribed. Determining the correct intensity is important because the specific stimulus that exercise elicits is dependent on where these intensities are located relative to the intensity domains (moderate, heavy, and severe) (Gaesser and Poole. 1996).

There are three distinct exercise intensity domains which are defined by their specific metabolic responses ($\dot{V}O_2$ and blood lactate) and times to exhaustion (Gaesser and Poole. 1996). The moderate exercise intensity domain includes intensities below the blood lactate threshold, where $\dot{V}O_2$ reaches a steady state within 2 to 3 minutes after the initial adjustment to exercise (Gaesser and Poole.1996). The boundary of the heavy exercise intensity domain occurs at the lowest intensity where blood lactate levels increase, but eventually stabilize. The ventilatory threshold (VT) and gas exchange threshold (GET), theoretically, demarcate the moderate from heavy domains, reflecting increased ventilation in response to excess CO_2 that is produced from the bicarbonate buffering of hydrogen ions generated as anaerobic glycolysis as it contributes to energy reconstitution (Gaesser and Poole,1996, Bergstrom et al.2013). Therefore, the heavy exercise intensity domain is defined as the lowest work rate at which blood lactate appearance exceeds its rate of removal and there is a sustained elevation of blood lactate for the remaining duration of exercise. Heavy intensity exercise demonstrates a delayed metabolic steady state, where $\dot{V}O_2$ and blood lactate reach approximately stable levels around 10 to 20 minutes after the onset of exercise (Gaesser and Poole 1988). The delayed steady state in $\dot{V}O_2$ is termed the $\dot{V}O_2$ slow component and is defined by a gradual increase in $\dot{V}O_2$ over time at a rate of >200 $ml \cdot min^{-1}$ (Poole et al. 1991). Heavy intensity exercise can typically be sustained for 30 to 60 minutes (Gasser and Poole 1996). Finally, the severe exercise intensity domain is defined as intensities where $\dot{V}O_2$ and blood lactate cannot be stabilized, but rather rise until fatigue at a point where $\dot{V}O_2$ achieves its maximum. Severe exercise intensities generally result in exhaustion within 20 minutes (Gasser and Poole. 1996). Typically, critical power (CP) and the critical velocity (CV) have been used to delineate the heavy from severe exercise intensity domains (Gaesser&Poole. 1996). However, the respiratory compensation point (RCP) may also estimate these values as it reflects the point where hydrogen ion production exceeds the capacity of the bicarbonate buffering system, which is demonstrated through a compensatory increase in minute ventilation (Wasserman,1978). Thus, fatigue thresholds such as the GET, VT, and RCP provide important information about the intensity of exercise relative to the exercise intensity domains and can be derived from a graded exercise test.

The metabolic ($\dot{V}O_2$ and blood lactate) responses that define the exercise intensity domains are based on a constant work rate of exercise. During exercise performed at a constant power output, above the VT or GET (Bull et al. 2008, Bull et al. 2000, Brickley et al 2002, Dekerle et al. 2003), there are predictable increases in HR, $\dot{V}O_2$, and the rating of perceived exertion (RPE) when exercise is maintained for 20 to 60 min. For constant work rate exercise within the heavy and severe domains, the tolerance of exercise is, in large part, related to the training status of the individual (Poole et al. 2016). That is, untrained to moderately trained individuals exercising at the top of the heavy or bottom of the severe domain (i.e., 10% above CP) may exhaust within 20 min, prior to achieving a physiological steady state and without $\dot{V}O_2$ reaching $\dot{V}O_{2max}$ (Bergstrom et al. 2017, Poole et al. 2016). Thus, it is important to note that, at an assigned vigorous intensity that is based on a $\%HR_{max}$ or % $\dot{V}O_{2max}$ (ACSM guidelines), the individual may be at a power output within the severe intensity domain, and it is likely exercise will not be sustained for >20 min. Consequently, exercise anchored by a power output reflects intensity-domain-specific metabolic and cardiovascular responses, which can increase muscular fatigue and decrease exercise sustainability outside the recommend range of 20-60 min. That is, depending on the assigned power output relative to the exercise intensity domains, $\dot{V}O_2$ and HR can increase to values that are greater than the range prescribed by the current exercise guidelines (Bull et al.2000, Housh et al.1991, Bull et al.2008). The specific metabolic demands of exercise are dependent on the exercise intensity domain, which cannot be delineated from a percent of the max or reserve capacity, but rather rely on the determination of fatigue thresholds (ref). Thus, the physiological demands of the current vigorous exercise recommendations are not well understood nor are they clearly defined on an individual basis.

The physiological demands of exercise may also vary depending on whether exercise is prescribed at a constant work rate (power output or velocity) or at a constant HR within the recommended range. Several studies (Mielke et al.2009, Bergstrom et al 2014, Bergstrom et al.2015) have presented evidence that there is a divergence in the patterns of responses for physiological and perceptual parameters when exercise is anchored by a physiological (HR) or perceptual (RPE) parameter, compared to when it is anchored by power output. For example, when exercise was anchored by HR, RPE increased, while power output, $\dot{V}O_2$, and minute ventilation ($\dot{V}_E$) decreased (Bergstrom et al.2014, Bergstrom et al.2015). There were also similar responses when exercise was anchored by RPE (Cochrane et al.2015). Specifically, the $\dot{V}O_2$, power output, and respiratory exchange ratio (RER) decreased. Thus, for exercise prescribed at a constant HR, it is possible for the decrease in power output and $\dot{V}O_2$ to result in a performance below the recommended intensity for improving CRF. Similarly, it is possible that the relative percentage of HR_{max} for vigorous exercise requires a HR that is too high to be sustained for the recommended minimum range (20 min). Therefore, it is important to identify an intensity that can elicit the desired metabolic stimulus, but low enough to meet the criteria for improving CRF (20-60 minutes). However, the specific physiological and perceptual responses to exercise anchored to HR within the recommended range for vigorous exercise (77-95% HR_{peak}) are currently unknown. Therefore, the purpose of this study was to examine the current ACSM guidelines for cardiorespiratory endurance by anchoring exercise at a HR in the lower, middle, and higher end of the range recommended for vigorous, cycle ergometry exercise (77-95% HR_{peak}). The overarching hypothesis was that exercise anchored to a HR in the middle of the recommend range will most closely reflect the vigorous metabolic stimulus and exercise duration, while the responses the lower and higher HR will fall outside the corresponding duration and metabolic stimulus recommendations. The following specific Aims were used to test this hypothesis.

Aim 1: Determine the metabolic ($\dot{V}O_2$) and perceptual (RPE) responses as well as the sustainability of exercise (time to exhaustion [T_{lim}]) anchored to HR at the lower (HR_L= 77%HR_{peak}), middle (HR_M=86% HR_{peak}), and higher (HR_H= 95%HR_{peak}) range recommended for vigorous exercise.

Hypothesis 1: The average metabolic ($\dot{V}O_2$) and perceptual (RPE) responses for the HR trials will be within the recommended range for vigorous exercise (64-90% $\dot{V}O_{2peak}$, RPE 14-17) at the HR_M (86%HR_{peak}) but will be lower than the recommend range for HR_L and higher for HR_H. The time to exhaustion will be the intensity dependent such that the lower HR (HR_L) will be sustained for 60 min for most participants, the sustainability of the middle HR (HR_M) will vary between 30 and 60 min, and the higher HR (HR_H) will not be sustainable for 30 min for most participants.

Aim 2: Determine if the $\dot{V}O_2$ and RPE response remain within the recommended ranges for vigorous exercise throughout the trials at HR_L, HR_M, HR_H. To achieve this aim, the time course of changes and the patterns of responses for $\dot{V}O_2$ and RPE for the composite (average of the whole sample) and on a participant-by-participant basis. In addition, to better inform these responses, the time course of changes and patterns of response for power output (PO), respiratory exchange ratio (RER), minute ventilation ($\dot{V}_E$), respiratory rate (RR), and metabolic efficiency ($\dot{V}O_2$/PO) will be examined for each HR trial.

Hypothesis 2: The $\dot{V}O_2$ and RPE will be within the recommended range at the start of each constant HR trial, but the $\dot{V}O_2$ and RPE will be lower than the recommended range at the end of exercise for HR_L trial and higher for HR_H trial. The $\dot{V}O_2$ and RPE responses for exercise at the HR_M (86%HR_{peak}) will be consistent with vigorous exercise range for the entire trial. The metabolic ($\dot{V}O_2$ and RER) responses will decrease as power output is reduced to maintain HR in an intensity specific manner. That is, greater power output and metabolic reductions will occur for the HR_H and HR_M, compared to HR_L. Across all intensities, the $\dot{V}_E$ will decrease, but the RR will increase. The RPE will increase at each HR, despite reductions in power output.

Aim 3: Determine the time spent in the severe (>RCP), heavy (<RCP, >VT), and moderate (<VT) intensity domains for the composite and on a subject-by-subject basis during each of the constant HR trials.

Hypothesis 3: The power output for the HR_H will be in the severe domain, while power output for the HR_M and HR_L will be in the heavy domain for most of the participants at the start of exercise. The power output will be reduced throughout the trial so that participants end in the heavy or moderate domain and the most time during exercise will be spent in the severe domain for HR_H and the heavy domain for HR_M and HR_L.

CHAPTER 2. REVIEW OF LITERATURE

2.1 Current Exercise Guidelines for Cardiorespiratory Fitness

Garber et al. 2011

The purpose of this position stand was to provide guidance to professionals who prescribes exercise to healthy adults of all ages. In this paper the authors demonstrated the beneficial effects of exercises and indicated the benefits of exercises that far outweigh the risks in most adults. Specifically, programs of regular exercise that includes cardiorespiratory, resistance, flexibility, and neuromotor exercise can help improve and maintain physical fitness for most adults. The American College of Sports Medicine (ACSM) recommends that most adults participate in moderate intensity exercise for ≥ 30 min·d-1 on ≥ 5d·wk-1 for a total of ≥ 150 min·wk-1, vigorous intensity cardiorespiratory exercise for ≥ 20min·d-1 on ≥ 3d·wk-1 for a total of ≥ 75min·wk-1, or a combination of both exercise intensity exercise to achieve a total of energy expenditure of ≥500-1000 MET.min.wk-1. There are several methods of estimating relative exercise intensity during cardiorespiratory exercise including the oxygen consumption ($\dot{V}$O2R) and heart rate (HRR) reserve methods, the percent of the maximum HR (%HRmax) and $\dot{V}$O2 ($\dot{V}$O2max), and the rating of perceived exertion (RPE). Each of these methods for prescribing exercise intensity have been shown to be efficient and can be recommended when prescribing exercise for an individual. It is also important to keep in mind that relationships between actual energy expenditure HRR, $\dot{V}$O2R, %HRmax, and % $\dot{V}$O2max can vary based on the exercise test protocol, age, body composition, fitness level, and other factors. The authors also confirmed that no study have compared all the methods of measurement of exercise intensity simultaneously, thus it cannot be assumed that one method of determining exercise intensity is necessarily equivalent to that derived using another method. Even though, these recommendations cannot be generalized for everyone the authors suggested that more exercise is required to improve cardiorespiratory fitness and cardiometabolic fitness than it is to maintain these improvements.

Gellish et al. 2007

The purpose of this study was to examine the relationship between age and maximal heart rate (HR_{max})during exercise to verify HRmax prediction equations use to prescribe exercise intensity. The authors examined records from 132 individuals (44±9.6 years) of both sexes with a broad range of age and fitness levels who had multiple GXT over the past 25 years. The HRmax prediction and HRmax were developed using a linear mixed-models statistical analysis approach. Males exhibited a lower average resting HR (64.2±10.5 $b \cdot min^{-1}$), greater BMI (Males=25±2 $kg \cdot m^{-2}$, Females=21.5±1.9 $kg \cdot m^{-2}$) and higher average of $\dot{V}O2max$ (Males=43.7±7 $ml \cdot kg^{-1} \cdot min^{-1}$, Females=36.4±7.2) than females. Clinical measurements obtained during the administration of the GXTs included in this longitudinal study resulted in the generation of a univariate prediction model: HRmax = 207 - 0.7 x age. As a result, there were noticeable differences, where the linear formula predicts an HR_{max} that is 3 $b \cdot min^{-1}$ lower than the standard formula (220 - age) would calculate. The authors concluded he relationship between age and HRmax during exercise developed in this longitudinal study has resulted in a prediction equation appreciably different from the conventional HR_{max} formula (220 - age) often used in exercise prescription, and it confirms findings from recent cross-sectional investigations of HR_{max}.

Hill et al. 2016

The purpose of this study was to determine how well the age predicted HRmax estimates actual HR_{max} for upper body exercise in healthy young and older adults. Thirty young (20± 2 years), and 20 elderly adults (66±6 years) performed an incremental exercise tests on a conventional arm crank ergometer. To allow lower power outputs, the older adults performed the test on an electrotonically braked arm crank ergometry (ACE) with an initial power output of 20 W. However, for the younger individuals the protocol started with an initial power output of 50W with an increment of 20 W every 2 min until exhaustion. All participants attained an RER ≥1.15 and a RPE of at least 18 (6-20 Borg scale) at exhaustion, this was similar between younger and older subjects. The HRmax prediction equation based on lower body cycle ergometer significantly overestimated the measured HR_{max} for arm crank in both older and younger subjects. Th authors findings suggest that traditional prediction equation for HR_{max} significantly overestimate the true HR_{max}, and future research should focus on developing a formula specifically developed for upper body exercise testing.

Hofmann et al. 2001

The purpose of this study was to investigate the influence of the time course of the heart rate performance curve (HRPC) on the accuracy of target training heart rate. Sixty-two healthy males' subjects performed an incremental cycle ergometer exercise test until voluntary exhaustion. The subjects were divided into four groups based on the HPRC. The groups were then classified in regular response (khr2 >0.3), indifferent responses

(0<khr2<0.2), linear heart rate response (khr2=0.2), and inverted HR response (khr2<0). Turn point in the time course of HR and blood lactate were assessed by linear regression. The HR at blood lactate point 1 (LTP1) and HR_{max} were not significantly different among all four groups, but HR at lactate point 2 (LTP2) depends on the time of course and were significantly different. The authors findings suggested that HR_{max} method should be adapted to reflect the relationship more accurately between HR and power.

Cunha et al. 2010

The purpose of this study was to determine whether different approaches used to determine $\dot{V}O_2$ max protocols and resting $\dot{V}O_2$ influence the relationships between percentage of heart rate reserve (%HRR), maximum heart rate (%HR_{max}), maximal oxygen uptake (%VO_{2max}) and oxygen uptake reserve (%VO_2R). Thirty-three healthy male (21± 4 years) performed a maximal treadmill protocols (ramp and Bruce) to assess HRmax and VO_{2max}, all of the subjects were involved in aerobic activities 20-60 min for 3-5times per week for at least six months before the study. Three approaches were adopted to assess the resting $\dot{V}O_2$: the resting $VO_{2standard}$ (24h abstention from exercise, alcohol, soft drinks, or caffeine were required) $\dot{V}O_2$ sitting and the $\dot{V}O_2$ standing (were both 5 mins before exercise). The results showed that %HRR was closer to % VO2max than %VO_2R for the ramp protocol. While the Bruce protocol resulted to a stronger interclass correlation (ICC), the ramp protocol produced higher VO_{2max} with a smaller production of errors. The authors findings suggested that aerobic exercise prescription should rely on %Vo2max and %HRR since this relationship was stronger than the %VO2R - %HRR relationships.

Strath et al. 2000

The purpose of this study was to examine the relationship between heart rate (HR) and $\dot{V}O_2$ during field and laboratory exercise. Sixty-one people participated in that study including thirty-one men (41$\pm$13 years) and 30 women (40$\pm$12 years). The HR and $\dot{V}O_2$were measured continuously during the 15min of performing a task such as (vacuuming, sweeping, moping, trimming, gardening, playing with animal in the yard, etc.), for each subject the mean HR and $\dot{V}O_2$ were computed from 5 to 15 min for each activity, then a linear regression analysis was performed to demonstrate the relationship between the energy expenditure (EE) and HR. The correlation between HR and $\dot{V}O_2$ showed a positive linear correlation with HR accounting for 47% of the variability in $\dot{V}O_2$. The authors findings indicated that HR was shown to be a moderate physiological indicator of $\dot{V}O_2$ and EE, during a variety of lifestyle activities.

Lambrick et al.2009 (EJAP)

The purpose of this study was to assess whether $\dot{V}O_{2max}$ could be accurately estimated from submaximal heart rate (HR), and the ratings of perceived exertion (RPE) from a single bout of moderate cycle ergometer exercise for low fit women. Eleven women (31.5±10.8 years) participated performed a graded ramp exercise test to establish the $\dot{V}O_{2max}$. This test started with a 2 min baseline measurement at 0 W and was increase every 4s (15 $W \cdot min^{-1}$) until $\dot{V}O_{2max}$ was reached. The author determined $\dot{V}O_{2max}$ as a peak or plateau in oxygen consumption, a HR within ±10 $b \cdot min^{-1}$ of the age conventional age predicted maximum, and an RER value that exceeded 1.15. The $\dot{V}O_{2max}$ was predicted from both the submaximal $\dot{V}O_2$ corresponding to the gas exchange threshold and RPE of 13. There was significant difference between measured (30.9± 6.5ml $kg^{-1}min^{-1}$) and predicted

$\dot{V}O_{2max}$. The authors concluded that RPE is a great tool that can be easily be used as a adjunct to HR, and provide supplemental information that is superior to using HR alone.

Summary

The articles in this section provide evidence of the beneficial effects of cardiorespiratory endurance exercises based on the current American College of Sports Medicine (ACSM) exercise guidelines (Garber et al.2011). Specifically, the recommendations for improving cardiorespiratory fitness include an intensity of at least 45% oxygen uptake reserve ($\dot{V}O_2R$), 64-76% of heart rate maximum (HR_{max}) and 46-63% of $\dot{V}O_{2max,}$ performed for 30 min, most days of the week (Garber et al.2011). Several methods can be used to estimate the relative exercise intensity such as HR, rating of perceived exertion (RPE), and %$\dot{V}O_{2max}$ each of these methods is shown to be efficient and can be beneficial when prescribing exercise for an individual (Garber et al.2011). The directly measured HR_{max} is preferred method for determining exercise intensities for exercise prescription based on HR, but when a direct measure of HR_{max} is not feasible, the estimation of HR_{max} is acceptable. An equation used to calculate the HR_{max}(207-(0.7×age) (Gellish et al. 2011) based on the longitudinal data has been shown to be more accurate than conventional HR_{max} formula (220-age). When looking at upper body exercise a new HRmax equation should be developed because the HR_{max} prediction equation tends to overestimate the actual HRmax for this modality (Hill et al. 2016). It has also been shown that, based on the heart rate performance curve on the accuracy of target HR training, the HR_{max} should be adapted to reflect a more accurate relationship between the HR and power output (Hofmann et al. 2001). The rating of perceive exertion (RPE) can be used as an adjunct to HR and provide supplemental information that is superior to using HR alone.

The overload principle of training states that exercise below a minimum intensity or threshold will not challenge the body sufficiently to result in a change in physiologic parameters including an increase of volume of oxygen per unit of time. Therefore, Cahuna et al. (2010) stated that aerobic exercise prescription should rely on %$\dot{V}O_2$max and %HRR since this relationship was confirmed to be stronger than the relationships between % $\dot{V}O_2$R and %HRR. From their task method protocol which included tasks of daily living (vacuuming, sweeping, moping, etc.), Strath et al. (2000) indicated that HR was shown to be a moderate indicator of $\dot{V}O_2$ and energy expenditure (EE) during a variety of lifestyle activities. Thus, taken together the articles in this section highlight the recommendations exercise prescription for improving cardiorespiratory fitness.

2.2 Exercise Intensity Domains and Fatigue Thresholds

Gaesser & Poole.1996

The purpose of this paper was to define the $\dot{V}O_2$ slow component and describe the $\dot{V}O_2$ characteristic across the exercise intensity domains. The authors defined the $\dot{V}O_2$ slow component as the continued rise of lactate threshold beyond the 3rd minute of exercise. The three intensity domains (moderate, heavy, and severe) are defined with respect to the $\dot{V}O_2$ intensity and the lactate threshold. The moderate intensity domain is defined as work rate that can be performed below the lactate threshold and, at a constant load the $\dot{V}O_2$ will increase and reach a steady state in about 3 min. The heavy domain is defined as the lowest work rate at which blood lactate increases above resting levels and the highest work rate at which blood lactate concentration reaches a steady state level. The heavy exercise intensity was also defined as a point where the $\dot{V}O_2$ slow component appears and contributes to a delayed response of the steady state. Furthermore, the domain of severe intensity exercise was defined at the point where $\dot{V}O_2$ and blood lactate cannot be stabilized, but rather rise until fatigue at a point where $\dot{V}O_2$ achieve its maximum. The authors concluded the mechanism accounting for $\dot{V}O_2$ slow component is within the muscle fiber, and the integration of electromyographic (EMG) data pointed at a change in the motor unit firing frequency during heavy and severe exercise intensity domain. The authors also concluded an increase in mitochondrial content in type I, and II muscle fibers may play a role in the attenuation of the $\dot{V}O_2$ slow component. Thus, this article highlights the unique metabolic responses across three exercise intensity domains, moderate, heavy, and severe, that inform the stability of exercise within each domain.

Beaver et al. 1986

The purpose of this study was to investigate the change in respiratory gas exchange during an incremental exercise test to derive the mathematical model based on buffering of lactic acid which could locate the anaerobic threshold (AT). Ten healthy subjects (19 to 39 years) participated in the study, each subject performed an incremental exercise test on a cycle ergometer with a work rate increased in increments of 15W/min. Gas exchange was measured from a mouthpiece connected to a turbine for continuous measurement of O_2, CO_2, and N_2 partial pressure and the data were analyzed using a computer to give estimates of the AT by the V-slope method for each subject. The mean gas exchange AT was found to correspond to a small increment of lactate above the lactate threshold (0.50 ± 0.34) and was not significantly different from the HCO_3 threshold. The mean $\dot{V}O_2$ at AT computed by the V-slope method was reliable, and the respiratory compensation point (RCP) was consistently higher than the AT (2.51 ± 0.42 vs 1.83 ± 0.30 l/min of $\dot{V}O_2$). The authors concluded that the V-slope analysis which detects the increased of CO_2 production from buffering metabolic acid addresses the mechanism of the anaerobic threshold and it is applicable.

Bergstrom et al. 2013

The purpose of this study was to compare the critical power (CP) from the 3-min test to the power outputs associated with the thresholds determined from gas exchange parameters that have been used to demarcate the exercise intensity domain including respiratory compensation point (RCP), gas exchange threshold (GET), and ventilatory threshold (VT). The GET was defined as the $\dot{V}O_2$ value using the V-slope method ($\dot{V}CO_2$) vs $\dot{V}O_2$. The RCP was defined as the relationship between ventilatory equivalent for oxygen uptake ($\dot{V}_E$) vs $\dot{V}O_2$. The VT was defined as the point of increase in the $\dot{V}_E/\dot{V}O_2$ vs $\dot{V}O_2$. Twenty-eight subjects (23.3$\pm$3.3 years) performed an incremental test to exhaustion on a calibrated electronically braked cycle ergometer at a pedal cadence of 70rev/min. The test began at 50 W, and power output was increased by 30 W every two minute until voluntary exhaustion, or the subject pedal rate fall below 70 rev·min.It was reported that there was no significance difference between the CP (187$\pm$47 W) and the power output associated with the RCP (190$\pm$49W) or between the power output associated with GET (139$\pm$37 W) and VT (145$\pm$37 W).However, the power output associated with the GET and VT were significantly less than the one at CP associated with the RCP. From these findings the authors suggested that CP and the RCP demarcate the heavy from severe exercise- intensity domain and result from a different mechanism of fatigue compared to the GET and VT.

Francis et al. 2010

The purpose of this study was to develop a modified version of 3-min all-out cycling test (3MT) to identify the exercise intensity domain using the end power (EP) of the 3MT. Sixteen competitive cyclists (32.4$\pm$ 8.7 years) completed an incremental load test, beginning with a warmup at 100 W and every 4 min thereafter the load was increase by 25 w. Power output at lactate threshold was determined by absolute 4 $mmol^{-1}$ onset of blood lactate accumulation and 1 $mmol^{-1}$ over exercise baseline. To determine peak lactate concentration blood samples were taken during the last 4 min of the work interval. Power output at ventilatory threshold (VT-PO) was computed based on the V-slope method and power output at VO_{2peak} (VO_{2peak}) was the mean power observed during the stage at which the peak O_2 consumption was recorded. Power output at VT was significantly greater than lactate threshold power output, the authors also indicated a significant effect between power output at lactate threshold, VT, VO_{2peak} and EP. The demarcation between moderate to heavy exercise intensity domains has been identified as the lowest work rate at which blood lactate appearance exceeds its rate of removal typically established using lactate or VT. The authors concluded the average power output over the last 30 s of the 3MT is correlated with power output at lactate and VT as well as power output at VO_{2peak}, therefore the EP from a single 3MT can be used to estimates the demarcations between the moderate to heavy exercise intensity domains.

Succi et al. 2020

The purpose of this study was to compare the initial metabolic $\dot{V}O_2$ 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). Nine moderately trained recreational runners (23$\pm$3 years) performed an incremental treadmill test to exhaustion to determine the $\dot{V}O_{2peak}$, GET, RCP, and VT. The test started with a velocity of 6.4 km$\cdot$hr^{-1} with a 0% grade, and as the test progressed, the velocity was increased by 1.6 km$\cdot$hr^{-1} every 2 minutes until 14.4 km$\cdot$hr^{-1}, once that stage was reached the velocity was no longer increased but the grade was increased by 2% every 2 minutes until exhaustion. The critical heart rate (CHR) was derived from the slope of the total heartbeats versus time to exhaustion relationship for four, constant power output trials to exhaustion. The GET was determined using a V-slope method and was defined as the $\dot{V}O_2$ corresponding to the point of intersection between $\dot{V}O_2$ and $\dot{V}CO_2$. The VT and RCP were determined using the same method except for using the ventilatory equivalent for oxygen uptake ($\dot{V}_E$) vs $\dot{V}O_2$, and $\dot{V}_E$ vs $\dot{V}CO_2$ plot respectively. The PWC$_{hrt}\dot{V}O_2$ were determined from 4 separate constant velocity. It was reported that the GET (38.44 ml$\cdot$kg$^{-1}\cdot$min^{-1},78%$\dot{V}O_{2peak}$), VT (37.36 ml$\cdot$kg$^{-1}\cdot$min^{-1},76% $\dot{V}O_{2peak}$) and PWC$_{hrt}\dot{V}O_2$ (38.26 ml$\cdot$kg$^{-1}\cdot$min^{-1},77% $\dot{V}O_{2peak}$) were not different but significantly lower than the RCP (44.70 ml$\cdot$kg$^{-1}\cdot$min^{-1},90% $\dot{V}O_{2peak}$). It was also reported that the CHR$\dot{V}O_2$ (40.09 ml$\cdot$kg$^{-1}\cdot$min^{-1},81%$\dot{V}O_{2peak}$) was not different from the GET. These findings concluded that the initial metabolic intensities at CHR and PWC$_{hrt}$ lie within the heavy and moderate intensity domains, which provide utility for varying fitness levels and training session goals.

Summary

The articles in this section described the physiological characteristics across the intensity domains and the use of fatigue thresholds as demarcations of the domains. There are three intensity domains, moderate, heavy, and severe that are defined with respect to $\dot{V}O_2$ and blood lactate responses (Gaesser et Poole. 1996). Beaver et al. (2011) reported that the V-slope method to determine the ventilatory threshold (VT), through the detection of an increase in CO2 production from the buffering of hydrogen ions, provided a reliable estimate of the mean $\dot{V}O_2$ at anaerobic threshold (AT) was reliable and the V-slope method detected an increase in CO_2 production from lactic acid buffering. The demarcation between moderate to heavy intensity domains has been identified as the lowest work rate at which blood lactate appearance exceeds its rate of removal, and is typically established using the anaerobic threshold (AT) (Beaver et al.1986,Francis et al.2010). It has been suggested that the VT and gas exchange threshold (GET) estimate the AT and the transition from the moderate to heavy domain, when ventilation increases in response to excess CO_2 that is produced from the bicarbonate buffering of hydrogen ions produced during anaerobic metabolism (Gaesser and Poole,1996, Bergstrom et al.2013). Beaver et al. (1986) reported that the V-slope method to determine the VT provided a reliable estimate of the mean $\dot{V}O_2$ at the AT. The boundary of the heavy and severe exercise intensity domain is the highest work intensity at which blood lactate and $\dot{V}O_2$ eventually reach steady-state levels (Gaesser and Poole, 1996; Bergstrom et al. 2013). In the severe exercise intensity domain $\dot{V}O_2$ and lactate fail to stabilize, both rise continuously until fatigue occurs, at which point $\dot{V}O_2$ reaches $\dot{V}O_{2max}$ (Gaesser&Poole. 1996). It has been suggested (Bergstrom et al. 2013) that the RCP reflects the demarcation of the heavy and severe domains as the point where hydrogen ion production exceeds the capacity of the bicarbonate buffering system which is demonstrated through a compensatory increase in minute ventilation. Succi et al. (2010) reported that there was no significant difference between the gas exchange threshold (GET) and the VT, but both thresholds were significantly lower than the RCP. Taken together, the articles in this section outline the unique metabolic characteristic of the exercise intensity domains which can be demarcated by fatigue threshold such as the GET, VT, and RCP

2.3 Responses at a Constant Power

Bull et al. 2000

The purposes of this study were to re-examine a previous study by using 5 mathematical model to compare critical power (CP) and anaerobic work capacity (AWC) estimates, and to determine time to exhaustion at the lowest estimate of CP. The 5 mathematical models used for the estimation of CP were the total work model (linear-TW), the linear P model (linear -P) the two-parameter nonlinear model (Nonlinear-2 model), a three-parameter nonlinear model (Nonlinear-3) and an exponential model (EXP). Nine subjects (25±3 years) performed a maximal incremental test to exhaustion on an electronically braked cycle ergometer to determine peak power (PP), $\dot{V}O_{2peak}$, and heart rate peak (HR_{peak}). There were 5 to 6 randomly ordered trials ranging from (PP-130 W to PP+ 50 W) and used for the estimation of CP. The authors described the linear – total work (TW) model as the linear relationship derived between the total work and the time to exhaustion(t) TW= (AWC+CP·t). The linear- P model was derived from using the relationship W=P·t, which was substituted for TW in the linear TW equation to provide the equation $P=(AWC\cdot t^{-1})+CP$. The nonlinear-2 model was based on the hyperbolic relation between P and t where t=AWC/(P-CP). The nonlinear-3 model is quite like the nonlinear-2 with the addition of a parameter maximal instantaneous power (P_{max}). The (P_{max}) allows for a time asymptote that is below the x axis where t=0 and provides a P_{max} value at the x-intercept. The P_{max} model equation is, t= (AWC(P-CP)$^{-1}$+ (AWC(Pmax-CP)$^{-1}$)). The exponential model (EXP) was like the nonlinear-3 model with the addition of a time constant (τ) to overcome the assumption of infinite power at a very short duration, P=CP+(P_{max}-CP) exp(-t/τ)). The subjects performed 2 trials at the lowest CP estimate for 60 minute or until exhaustion was reached. The nonlinear-3 model provided the lowest estimate of CP (180±26) for all subjects. There were 2 of the 9 subjects who were unable to complete the 60 minutes for both trials. The subjects who complete 60 minutes, had an HR of 166 ±10 b·min^{-1}, which represented 93±5% of HR_{peak} and 165±12 beats·min^{-1} for the second CP ride, which represented 91±5% of HR_{peak}. For the subjects who did not completed the 60 minutes the HR responses were 175±5 b·min^{-1} (96±1% of HR_{peak}) for trial 1 and 175±7 b·min^{-1} (97±6% of HR_{peak}) for trial 2. The RPE values for those who completed the 60 minutes during trial 1 and trial 2 were 19±1 and 17±3, respectively. The RPE for the 2 subjects who did not completed trial 1 and the three subjects who did not completed trial 2 were 19±1 and both trials. The authors findings indicated that CP did not represent a fatigueless task for all subjects. Thus, the mathematical models may provide the overestimation of CP during cycle ergometry exercise.

Bull et al. 2008

The purpose of this study was to compare the oxygen uptake ($\dot{V}O_2$) and heart rate (HR) responses at 5 estimates critical velocity (CV) and anaerobic running capacity (ARC) using different mathematical models. The first linear model was the total distance model (Lin-TD) based on the linear regression of total distance(TD) vs time (t)($TD = ARC +$

$CV \times t$). The second linear velocity (V) model was derived from the inverse of time model given the equation ($V = ARC \times \left(\frac{1}{t}\right) + CV$). The third model, but nonlinear, is based from the relationship between velocity and time to exhaustion ($t = ARC/(V - CV)$). The fourth model, which is also a nonlinear model includes a third parameter into the first nonlinear model, which is an upper limit where there an instantaneous velocity that can be achieved (Vmax) ($t = \left[\frac{ARC}{V - CV}\right] - \left[\frac{ARC}{Vmax - CV}\right]$). The fifth model is an exponential model which includes the Vmax parameter as well as a time constant (τ) ($V = CV + (Vmax - CV)\exp(-\frac{t}{\tau}$). Ten subjects (22±2 years) completed an incremental test to derived $\dot{V}O_{2max}$(51±6 ml·min^{-1}·kg^{-1})and HR_{max} (195±7 b·min^{-1}), followed by four to five randomly ordered constant velocity trials on a treadmill to estimate critical velocity (CV) using the 5 different mathematical models. The subjects performed five randomly trials to exhaustion at CV from each model. The three-parameter nonlinear provided the lowest estimate of CV compared to the other models. The time to exhaustion was significantly greater for the three-parameter nonlinear model (51.7±12.9 min) compared to all the other models, and a HR response (179±18 b·min^{-1}) was significantly lower than the HR_{max} from the incremental test. The $\dot{V}O_2$ values were significantly less for all models compared to the $\dot{V}O_{2max}$ from the incremental test. From these results, the authors concluded that CV does not represent an intensity that can be maintained for an extended period of time without fatigue.

Housh et al. 1991

The aim of this study was to examine the validity of the fatigue threshold (FT)(i.e., critical velocity) by determining the oxygen consumption ($\dot{V}O_2$), heart rate (HR) and lactate threshold. The FT test was defined as a test that involves a series of high-speed treadmill runs to exhaustion at several different velocities during which the time to exhaustion is recorded. Ten adults (21.1±1.3 years) performed a graded exercise test to determine the maximal oxygen consumption rate ($\dot{V}O_{2max}$) and a FT test. The test began at 6.4 km·hr^{-1} and increased 1.6km·hr^{-1} every three minutes up to 14.5 km·hr^{-1}, the intensity was then increase by 2% every three minutes. It was reported that there was significant difference between the $\dot{V}O_{2max}$ (49.5±1.9 ml·min^{-1}·kg^{-1}), HR_{max} (203±3 b·min^{-1}), and maximal plasma lactate (7.4±0.7mM) compare to the $\dot{V}O_2$ at FT (47.5±1.8 ml·min^{-1}·kg^{-1}) HR at FT (197±3 b·min^{-1}) and maximal plasma lactate at the FT (5.4±0.4mM). Based on these results, the authors concluded the FT is not a measure of the maximal running velocity that can be maintained for an extended period of time.

Brickley et al. 2002

The purpose of this study was to examine the physiological responses to exercise at critical power (CP). Seven trained males (23 ±3.1) completed five exercise tests an incremental ramp test to determine $\dot{V}O_{2max}$, and 3 exhaustive loads 95%,100%, and 120% peak power were used to determine CP. On a separate day the subjects exercised to exhaustion at their individually determined CP. At CP, the time to failure ranged from 20.02 min to 40.62 min. The $\dot{V}O_2$ and blood lactate increased from 3.7 l·min^{-1} to 4.13 l·min^{-1} and from 1.8 mmol^{-1} to 6.5 mmol, respectively, from the beginning to the end of the ride at the CP. The authors also reported an increase in heart rate from 120 b·min^{-1} at the beginning to 178 b·min^{-1} at the end of the ride at CP. The authors concluded that the CP is not an intensity that can be sustained for a long period of time, especially when exercising at a non-steady state

Dekerle et al. 2003

The purpose of this study was to investigate the use of critical power (CP) and ventilatory threshold (VT) as indicators of maximal lactate steady state (MLSS). Eleven healthy and well-trained male students (23±2.9) volunteered for this study. Each subject performed three sessions to determine $\dot{V}O_{2max}$, VT, MLSS, and CP. To determine $\dot{V}O_{2max}$, the subjects were encouraged to continue to work until they reached exhaustion during an incremental cycle ergometry test. The VT_1 was defined as the minimal load at which $\dot{V}_E/\dot{V}O_2$ exhibited a systematic increase without $\dot{V}_E$ /$\dot{V}CO_2$ increasing, the VT_2 corresponded to the minimal work rate at which the increase in $\dot{V}_E/\dot{V}O_2$ was accompanied with an increase in $\dot{V}_E$ /$\dot{V}CO_2$, and the MLSS was defined as the highest work rate that could be maintained for 30 min without an increase of lactate by more than 1.0mmol^{-1}. To determine CP, four rides to exhaustion at 90%, 95%, 100%, and 110% were used. The authors results found that the mean MLSS (239±21W) work rate was significantly lower than mean CP (278±22 W) but was located between mean VT_1(159±23W) and VT_2(286±28 W). The authors findings indicated that since CP and VT_2 were significantly higher than the MLSS, these thresholds (CP and VT_2) do not represent a maximal work rate that can be maintained for a long period of time without a continuous rise of blood lactate.

Summary

The studies in this section (Bull et all. 2000, Bull et al. 2008, Brickley et al. 2002, Dekerle et al. 2003) examined the physiological responses to exercise at a constant power output relative to critical power (CP) or critical velocity (CV). Critical power (CP) has been described as a maximum power output that can be maintain without exhaustion and has been suggested to demarcate the heavy from the severe domain (Brickley et al.2002). The CP can be determined from 5 different mathematical models, with the three-parameter (nonlinear-3) model typically providing the lowest estimate (Bull et al. 2000, Bull et al. 2008). It was shown (Bull et al. 2000), 7 of the 9 subjects were able to maintain at least 60 min of exercise at CP from the non-linear-3 model. It is also important to mention that the nonlinear-3 model represents a more sustainable intensity compared to the CP estimates from all other models (Bull et al.2008). Previous work (Brickley et al. 2002, Dekerle et al. 2003, Housh et al. 1991) indicated that CP and critical velocity (CV) estimated from linear mathematical models did not provide an estimate of the highest intensity that can be sustained for an extended period because $\dot{V}O_2$, blood lactate, and heart rate did not reach a steady-state response. In addition, (Brickley et al. 2002) reported that during constant-intensity $\dot{V}O2$ increased from 3.71 $L \cdot min^{-1}$ to 4.13 $L \cdot min^{-1}$ and the HR increased from a mean value of 120 $b \cdot min^{-1}$ to 178 $b \cdot min^{-1}$ after 20min of exercise. Thus, the physiological responses and sustainability of exercise are dependent on the relative intensity of the power output, with respect to the exercise intensity domains. Overall, exercise at CP and CV reflected exercise performed in the severe domain. However, it is possible that the physiological responses may reach a steady-state value based on the mathematical model used to estimate CP or CV.

2.4 Responses to Exercise Anchored to a Physiological Parameter

Kindermann et al. 1979

The purpose of this study was to examine physiological response during the constant heart rate (HR) vs constant velocity treadmill runs at a HR or velocity associated with anaerobic threshold (AT). Seven cross country skiers (20.9+- 1.7 years) completed runs on a treadmill until exhaustion where, HR, blood lactate, and the volume oxygen consumed ($\dot{V}O_2$) were measured. The treadmill speed, $\dot{V}O_2$, and heart rate were used to determine the AT. The AT was defined as the point where blood lactate reached 4 mmol. L^{-1}. A second 30 min running test was performed at the velocity associated with the AT. The mean maximal values for $\dot{V}O2$ intake, HR, and lactate concentration were 64.6 $ml \cdot min^{-1} \cdot kg^{-1}$, 192 $b \cdot min^{-1}$, and 11.08 mmol, respectively. The mean velocity associated with the aerobic threshold was 84% of the peak power while the mean HR was 174 b·min ^{1}, and the constant HR runs was 192 b·min ^{1} The authors findings showed that endurance training done with an intensity leading to lactate levels in range of 4 mmol can be maintained for 45 to 60 min. They also found that to maintain a constant HR that is associated with AT the velocity must be decreased. The authors concluded that the HR that is in association with AT can often be used for endurance training.

Ribeiro et al. 1986

The purpose of this study was to determine the metabolic and ventilatory responses to steady state submaximal exercise on the cycle ergometer. Eight physically active male subjects participated in this study, their (mean ±SD) age, height, and weight were (24 ± 3years), (177±3 cm), and (75±5 kg, respectively). The subjects performed 6 exercise tests on an electrically braked cycle ergometer maintaining a pedaling rate of 70 rev·min ^{1}. First, the subjects completed an incremental cycle ergometer test to determine $\dot{V}O_2max$, aerobic threshold (AeT), and anaerobic threshold (AnT), followed by a test to determine the steady state $\dot{V}O_2$ at AeT and AnT. Four trials were performed where power output was adjusted to maintain a steady state $\dot{V}O_2$ for 30 min at values equivalent to the AeT, between the AeT and AnT (AeTanT), at the AnT, and between AnT and $\dot{V}O_2$ max (AnTmax). Ventilatory variables were calculated online by a microcomputer, and ECG were recorded for the determination of heart rate. The maximal oxygen uptake for the subjects averaged (58± 8 ml.kg.min) and blood lactate level of (4 mmol) during constant $\dot{V}O_2$ trials. The authors found steady state blood lactate levels and ventilatory responses may occur at exercise intensity including AnT during prolonged exercise. They also found out at intensity above AnT lactate accumulation and ventilatory response progressively increase with early onset of fatigue ≥16 min of exercise.

Mielke et al. 2011

The purpose of this study was to determine if the mathematical model that has previously been used to estimate the critical power (CP) could be applied to heart rate (HR) to estimate the critical heart rate (CHR). The authors compared the CHR to the HR value at the ventilatory threshold (VT_{HR}), respiratory compensation (RCP_{HR}) and CP to (CP_{HR}) to determine if the exercise intensity at the CHR demarcated fatiguing from non-fatiguing work. Fifteen women (21.7 ± 2.1 years) accomplished an incremental test to exhaustion to determine the VO2peak, VT_{HR}, and RCP_{HR}. For this study, 4 exhaustive workbouts were performed at different power outputs and at each power output the time to exhaustion and 5 second average heart rate values were recorded to determine CP and CHR. The CHR was defined as the slope coefficient between the total heartbeat to exhaustion (HB_{lim}) and time to exhaustion (T_{lim}) and CP was the slope coefficient between the total work and T_{lim}. The RCP_{HR} and VT_{HR} were determined from the breakpoint in the $\dot{V}_E$ vs $\dot{V}CO_2$ and $\dot{V}_E$ vs $\dot{V}O_2$

relationships, respectively and by plotting the HR values from the incremental test against $\dot{V}O_2$ value. The mean CHR (172± 11bpm) was not different from the RCP_{HR} (172±9bpm) but was higher than CP_{HR} (154±10bpm) and VT_{HR} (152±12bpm). The authors findings suggested the mathematical model used to determine the CP could be applied to HR to estimate the CHR, and the CHR estimates a non-fatiguing HR that could be maintained for an extended period.

Bergstrom et al. 2015b

The purposes of this study were to determine if the mathematical model used to estimate critical power could be applied to HR measurement to derive a fatigue threshold called the critical heart rate (CHR) for treadmill running and examined the time to exhaustion and $\dot{V}O_2$ responses during the runs at CHR. Thirteen runners (23±4 years) performed an incremental treadmill test to exhaustion and 4 constant velocity runs to exhaustion on separate days. The total number of heart beats (HBlim) was calculated as a product of the 5-second HR average and the time to exhaustion (Tlim). The CHR was determined as the slope coefficient between the (HB_{lim}) and (T_{lim}). The $\dot{V}O2$ was recorded during the constant HR run at CHR. The mean CHR occurred at 176±7 $b{\cdot}min^{-1}$ and was sustained for 47.84 ± 11.04 min. There were quadratic decreases in velocity and $\dot{V}O_2$ during the runs at CHR. Furthermore, a one-way repeated measure ANOVA was used and examine differences in the $\dot{V}O_2$ values at the start and end of the CHR run compared to $\dot{V}O_2$peak. Specifically, the $\dot{V}O_2$peak was greater than the $\dot{V}O_2$ at the start and end of the run and the $\dot{V}O_2$ at the start of the run was greater than the $\dot{V}O_2$ at the end. The authors findings indicated the mathematical model used to derive the CHR could be applied to treadmill running, and the treadmill- based CHR represents the maximal HR that could be maintained for an extended period without fatigue.

Bergstrom et al. 2015a

The purpose of this study was to examine: 1) the sustainability of the critical heart rate (CHR) minus 5 b·min^{-1} (CHR-5) and CHR plus 5 b·min^{-1} (CHR+ 5); 2) the ratings of perceived exertion (RPE), velocity, $\dot{V}O_2$, minute ventilation ($\dot{V}$E) breathing frequency (f_b), and electromyographic amplitude (EMG AMP) and mean power frequency (MPF). Eight runners (23 ± 3 years) performed a series of four exhaustive, constant velocity runs to determine the CHR. The RPE, velocity, $\dot{V}O_2$, $\dot{V}_E$, f_b, and EMG AMP were recorded during runs at CHR-5 and CHR+5. The mean percent changes from when CHR – 5 was reached to the end of the run for RPE, velocity, $\dot{V}O_2$, $\dot{V}_E$, f_b,, EMG AMP, and EMG MPF were 9± 23 %, -23± 4 %, -12± 6 %, -18 ±6 %, 16± 16 %, -10 ±14 %, and 5 ±10 %, respectively. While the mean percent changes from when CHR + 5 was reached to exhaustion for RPE, velocity, $\dot{V}O_2$, $\dot{V}_E$, f_b,, EMG AMP, and EMG MPF were 18 ±5 %,-17 ± 11 %, -8 ±10 %,-10 ±17 %,12 ±18 %,-3 ±13 %, and -6 ±16 % respectively .The regression analyses for the mean responses during the continuous runs at CHR+ 5 indicated there was no change in HR, but a linear increase in RPE and a quadratic increase in f_b.. It was also reported that there was a quadratic increase in velocity, $\dot{V}O_2$, $\dot{V}_E$, and EMG AMP at CHR+5. The authors findings indicated at CHR-5 the time to exhaustion and the $\dot{V}O_2$ responses represented a sustainable intensity within the heavy domain. However, the reduction in velocity and muscle activation was likely great enough that afferent feedback and RPE were not related to metabolic stimuli. These findings suggested the mechanical feedback from fatiguing muscle could be an influence in the perception of effort but not a dominant mechanism during the initial portion of the run.

Summary

The articles in this section demonstrated how exercise intensities anchored to a physiological parameter can elicit different responses than continuous exercise at a constant power output or speed. For example, it was demonstrated that at a constant heart rate anchored to critical heart rate [CHR] and $\dot{V}O_2$ decrease throughout trials either on a treadmill (Bergstrom et al. 2015, Kindermann et al.1979) or a cycle ergometer (Mielke et al.2011). Despite these decreases in the metabolic demand the rating of perceived exertion (RPE) increased during trials at a constant heart rate (Bergstrom et al. 2015). Bergstrom et al. (2015) also noted that RPE was a consistent sign of fatigue due to metabolic and or mechanical sensory feedback via muscle afferents. Kindermann et al. (1979) demonstrated that endurance training anchored by physiological parameter such as lactate levels in range of 4 mmol can be maintained for 45-60 min. Furthermore, (Ribeiro et al.1986) mentioned, to maintain a steady state $\dot{V}O_2$ for 30 min, power output needed to be adjusted at values equivalent to the aerobic (AeT, moderate to heavy domain) or between the aerobic and anaerobic threshold (AeTAnT, heavy domain). Thus, exercise anchored to a physiological parameter reflects distinct alterations in metabolic and performance (power output, velocity, time to exhaustion) parameters compared to constant work rate exercise.

CHAPTER 3. METHODS

3.1 Experimental Design

This study included four visits with each visit separated by 24- 48 h. During the first visit the participant signed the informed consent, filled out the health history questionnaire, and completed a graded exercise test (GXT) to exhaustion on a cycle ergometer to determine the peak volume of oxygen consumed ($\dot{V}O_{2\ peak}$), peak heart rate achieved (HR_{peak}), and peak power output generated (PPO). Visits two through four consisted of 3, randomly ordered constant HR trials to exhaustion at 77% (HR_L), 86% (HR_M), and 95% (HR_H) of HR_{peak}, which fall with the range of values (77%-95%HR_{peak}) for vigorous exercise recommended by the ACSM. The term peak, rather than max, was used to this study to be consistent with the terminology used to describe the highest values obtained from a cycle ergometry graded exercise test, without a plateau in $\dot{V}O_2$ (Whipp &Ward. 1990). Power output was adjusted during these trials so that participants maintained the designated percentage of HR_{peak}. During each of the trials $\dot{V}O_2$, RER, $\dot{V}_E$, RR, HR, and RPE responses were recorded.

3.2 Participants

The sample size calculation for this study was based on previous work examining the changes in metabolic responses during constant HR exercise (Bergstrom et al. 2015, Succi Thesis), which demonstrated a range of $p\eta^2$ from 0.557 – 0.907. Utilizing the aforementioned $p\eta^2$, an a priori power analysis (alpha level = 0.05; power = 0.95) was conducted to determine the number of participants required for this study. The power analysis indicated a total sample size of 6 – 12 participants were required. Based on the results of the power analysis and potential attrition, 16 moderately trained participants aged 18-32 years were recruited for this study. However, four of the participants were excluded because their HR was outside of the required range (±2 $b \cdot min^{-1}$) to be considered a constant HR for one or more of the trials. Therefore, 12 participants were included in the final analyses. Participants were required to be moderately trained, which was defined as completing 30 minutes of physical activity a day for 5 days per week on most weeks for the past 6 months (ACSM textbook). The participants were instructed to avoid caffeine and alcohol 48 hours prior to the test and refrain to exercise 24 hours prior to testing. In addition, the participants were asked to avoid food ingestion 1 to 2 hours prior to each test. Participants were screened via questionnaire for known pulmonary, cardiovascular, metabolic, muscular and/or coronary heart disease**,** and all participants signed an informed consent prior to testing. This study was approved by the University of Kentucky Institutional Review Board.

3.3 Determination of $\dot{V}O_{2\,peak}$, HR_{peak}, Ventilatory threshold (VT), and respiratory compensation point (RCP)

The participants performed a GXT to exhaustion on a calibrated cycle ergometer (Lode, Corval, Groningen, Netherlands) to determine the $\dot{V}O_{2peak}$, RER_{peak}, $\dot{V}_{Epeak}$, RR_{peak}, HR_{peak}, and peak power output (PPO) as well as the VT and RCP. The ergometer seat height was adjusted so that participant's legs was near full extension at the bottom of the pedal revolution. Each participant was fitted with a nose clip, mouthpiece mounted to a headset (2700; Hans Rudolph, Kansas City, Missouri, USA) and a heart rate monitor (Polar Heart Watch system, Polar Electro Inc., Lake Success, New York, USA). Expired gas samples were collected and analyzed using a calibrated TrueMax 2400 metabolic cart (Parvo Medics, Sandy, UT). Prior to testing, the gas analyzers were calibrated to room air and gases of known concentration. The oxygen (O_2) and carbon dioxide (CO_2) parameters were expressed as 20-second averages (Robergs et al. 2010). Each participant was asked to give a rating of perceived exertion (RPE) during the last 10 seconds of each stage using the Borg 6-20 RPE scale (Borg 1970). The test began at 50 W at a pedal cadence of 70 rev·min^{-1}, and the power output was increased by 30 W every 2 min until voluntary exhaustion, or the participant could no longer maintain the designated 70 rev·min^{-1} pedal cadence for more than 10 seconds despite strong verbal encouragement. The $\dot{V}O_{2peak}$, RER_{peak}, $\dot{V}_{Epeak}$, RR_{peak}, and HR_{peak} were defined as the highest 20-second average $\dot{V}O_2$ RER, $\dot{V}_E$, RR, and HR value, respectively, recorded during the test. After the participant reached exhaustion, the participant performed a cool-down period on the cycle ergometer at a self-selected power output and duration. The ventilatory threshold (VT) and respiratory compensation point (RCP) were determined using a visual inspection method (Beaver et al. 1986). The VT was defined as the power output associated with $\dot{V}O_2$ corresponding to the point of intersection of two, separately derived regression lines of the $\dot{V}_E$ versus $\dot{V}O_2$ plot (Wasserman, 1978). Similarly, the RCP was defined as the power output associated with the $\dot{V}O_2$ value corresponding to the point of departure from linearity of $\dot{V}_E$ versus $\dot{V}CO_2$ plot (Wasserman, 1978).

3.4 Constant Heart Rate Trials

The $\dot{V}O_2$, RER, $\dot{V}_E$, RR, power output, RPE and time to exhaustion (T_{lim}) were examined during randomly ordered, continuous trials to exhaustion at 77% (HR_L), 86% (HR_M), and 95% (HR_H) of the participants HR_{peak}. During these trials, the cycle ergometer was set up for each participant as previous described and the participant was fitted with a Polar Heart Rate monitor. The participants completed a warmup at 50-100W for 3 minutes. To achieve the designated HR for each trial to exhaustion, the initial power output was set to the power output associated with the designated HR from the GXT. If the designated HR was not achieved within 5 minutes, the power output was gradually increased to elicit the designated HR. The participants pedaled at 70 rev·min^{-1} and the test was terminated when the participants could no longer maintain that cadence for 10 seconds despite verbal encouragement or after 60 min of exercise. The $\dot{V}O_2$, HR, and power output were recorded as 20 second averages. The RPE was taken every minute. The time spent in each exercise intensity domain was calculated as the sum of the time that the power output corresponded to severe (>RCP), heavy (<RCP, >VT), and moderate (<VT) domains and included the time to get to the designated HR.

3.5 Statistical analyses

The mean ± standard deviation were calculated for each variable (T_{lim}, $\dot{V}O_2$, HR, power output, and RPE) at exhaustion for HR_L, HR_M, and HR_H. For Aim 1, separate, one-way repeated measures (RM) ANOVAs with Bonferroni post-hoc pairwise comparisons were used to examine the T_{Lim} (calculated as the time at each HR, excluding the time to get to the HR) as well as the average, normalized (% peak value) $\dot{V}O_2$, power output, and RPE from the entire constant HR trails (HR_L, HR_M, HR_H). To examine the time course of changes, each dependent variable ($\dot{V}O_2$, RPE, power output, $\dot{V}_E$, and RR,) was normalized as a percentage of the peak value from the GXT and time was normalized as a percentage of $T_{lim,}$ to account for the differences in time to exhaustion among the participants. There were 10 data points used in the analyses (10, 20, 30, 40, 50, 60, 70, 80, 90, 100%). For Aim 2, the time course of changes in normalized $\dot{V}O_2$, RPE, PO, RER, $\dot{V}_E$, and RR during each of the three constant HR trails were examined with separate, 3 (Intensity; HR_L, HR_M, HR_H) x 10 (Time Course; $\%T_{lim}$ [10, 20, 30, 40, 50, 60, 70, 80, 90, 100]) repeated measures ANOVAs. In addition, metabolic efficiency ($\dot{V}O_2$/PO) was examined using a 3(Intensity; HR_L, HR_M, HR_H) x 2(Time; start [$10\%T_{Lim}$], end [$100\%T_{Lim}$]). Follow-up analyses included 1-way RM ANOVAs and post-hoc t-tests with a Bonferroni corrected alpha across to examine response across time ($p<0.005$) and among intensities ($p<0.017$). Polynomial regression analyses (linear and quadratic) were used to examine the patterns of responses for the normalized composite $\dot{V}O_2$, HR, power output, and RPE versus normalized time for each constant HR trial. To examine Aim 3, the time spent in each domain was determined for each subject at each HR, which included the time to reach the required HR. Mean comparisons for the total time (min) in each domain were made using a 3 (Intensity; HR_L, HR_M, HR_H) x 3 (Domain; moderate, heavy, and severe) repeated measures ANOVA with follow-up, 1-way repeated measures ANOVAs and post-hoc t-tests with a Bonferroni corrected alpha ($p<0.017$). An alpha level of $p \leq 0.05$ was used to determine statistical significance for all ANOVAs. All analyses were conducted using Statistical Package for the Social Sciences software (v.21.0. IMB SPSS Inc., Chicago, Illinois, USA).

CHAPTER 4. RESULTS

4.1 Graded Exercise Test

The descriptive characteristics of the participants (n=12) are presented in Table 1. The (mean±SD) and range for each variable ($\dot{V}O_{peak}$, RER_{peak}, $\dot{V}E_{peak}$, RR_{peak}, HR_{peak}, T_{Lim}, and RPE_{peak}) from the incremental test are included in Table 2. The mean VT and RCP occurred at 22.78±4.32 $ml \cdot kg^{-1} \cdot min^{-1}$ and 29.91±6.04 $ml \cdot kg^{-1} \cdot min^{-1}$, respectively, and represented a mean of 64±8%, and 83±7% of the $\dot{V}O_{2peak}$ from the GXT, respectively (Table 3). The mean power output at the VT (PO VT) and RCP (PO RCP) occurred at 128±21.05 W and 181±33.24 W, and had mean GXT peak power outputs of 67±12% and 86±12%, respectively (Table 3).

4.2 Constant Heart Rate Trials: Times to Exhaustion, VO_2 and RPE responses (Aim 1)

The results of the one-way repeated measures ANOVA indicated significant differences ($F=26.196$, $p \leq 0.001$, $\eta_p^2=0.704$) among the T_{lim} at HR_L, HR_M, and HR_H. Post-hoc, t-tests with a Bonferroni corrected alpha ($p<0.017$) indicated that the T_{lim} for HR_L (53.42±13.19 min) and HR_M (46.89±18.89 min) were significantly longer (both $p<0.001$) than the time to exhaustion at HR_H (27.05±18.00 min). There was, however, no significant difference ($p=0.157$) in the times to exhaustion for HR_L and HR_M. The individual responses as well as the average $\dot{V}O_2$, power output, and RPE for the entire trial, as a percent of the peak value, are presented in Tables 4, 5, and 6 for the constant HR_L, HR_M, and HR_H trials, respectively.

4.3 The time course of changes and patterns of responses (Aim 2)

4.3.1 Volume of Oxygen ($\dot{V}O_2$)

A 3 (Intensity; HR_L, HR_M, HR_H) x 10(Time; $\%T_{lim}$ [10-100]) repeated measures ANOVA to examine changes in $\dot{V}O_2$ indicated there was no two-way interaction (F=2.077, p=0.114, η_p^2=0.159, Greenhouse-Geisser correction). There were, however, main effects for intensity (F=110.0179, p<0.001, η_p^2=0.909) and time (F= 59.045, *p*<0.001, η_p^2=0.843). The main effect for time and post-hoc t-tests with a Bonferroni corrected alpha (*p*<0.005) indicated that $\dot{V}O_2$, collapsed across intensity, was significantly lower than the initial value (10%) from 20-100% of T_{lim} (*p*<0.001 for all comparisons) (Figure 1). The results of the polynomial regression analyses indicated that there was a negative quadratic relationship (R^2=0.979) for $\dot{V}O_2$ ($\%\dot{V}O_{2peak}$) versus time (collapsed across intensity). The individual $\dot{V}O_2$ ($\%\dot{V}O_{2peak}$) responses for the HR_L, HR_M, and HR_H trails are provided for descriptive purposes in Tables 7, 8, and 9, respectively.

The main effect for intensity and post-hoc t-tests with a Bonferroni corrected alpha (p<0.017) indicated that the relative $\dot{V}O_2$ for the HR_L (53.92±2.24 $\%\dot{V}O_{2peak}$) was significantly lower than the relative $\dot{V}O_2$ for HR_M (63.89±3.73$\%\dot{V}O_{2peak}$, *p*<0.001) and HR_H (80.35±3.88$\%\dot{V}O_{2peak}$, p<0.001). In addition, the relative $\dot{V}O_2$ for the HR_M trial was significantly (*p* <0.001) lower than the HR_H trial.

4.3.2 Rating of Perceived Exertion (RPE)

A 3 (Intensity; HR_L, HR_M, HR_H) x 10(Time; $\%T_{Lim}$ [10-100]) repeated measures ANOVA to examine changes in RPE indicated there was no two-way interaction (F=1.281, p=0.296, η_p^2=0.104, Greenhouse-Geisser correction). There were, however, main effects for intensity ($F=41.175$, $p<0.001$, $\eta_p^2=0.789$) and time ($F= 27.312$, $p<0.001$, $\eta_p^2=0.713$). The main effect for time and post-hoc t-tests with a Bonferroni corrected alpha ($p<0.005$) indicated that RPE, collapsed across intensity, was significantly higher than the initial value (10%) from 30-100% of T_{lim} $p<0.001$ (Figure 2). The results for the polynomial regression analyses indicated that there was positive, linear relationship ($r^2=0.988$) for RPE ($\%RPE_{peak}$) versus time (collapsed across intensity). The individual RPE (absolute value) responses for the HR_L, HR_M, and HR_H trails are provided for descriptive purposes in Tables 10, 11, and 12, respectively.

The main effect for intensity and post-hoc t-tests with a Bonferroni corrected alpha ($p<0.017$) indicated that the relative RPE for the HR_L ($62.39\pm6.55\%RPE_{peak}$) was significantly lower than the relative RPE for HR_M ($76.96\pm7.15\%$ RPE_{peak}, $p=0.006$) and HR_H ($91.75\pm6.41\%RPE_{peak}$, $p<0.001$). In addition, the relative RPE for the HR_M trial was significantly ($p<0.001$) lower than the HR_H trial.

4.3.3 Power Output (PO)

A 3 (Intensity; HR_L, HR_M, HR_H) x 10(Time; $\%T_{Lim}$ [10-100]) repeated measures ANOVA to examine changes in PO indicated there was no two-way interaction ($F=0.981$, $p=0.429$, $\eta_p^2=0.082$, Greenhouse-Geisser correction). We found main effects for intensity ($F=104.101$, $p<0.001$, $\eta_p^2=0.904$) and time ($F= 44.555$, $p<0.001$, $\eta_p^2=0.802$). The main effect for time and post-hoc t-tests with a Bonferroni corrected alpha ($p<0.005$) indicated that PO, collapsed across intensity, was significantly lower than the initial value (10%) from 20-100% of T_{lim} ($p=0.0002$ to 0.0014) (Figure 3). The results of the polynomial regression analyses indicated that there was a negative, quadratic relationship (R^2=0.957) for PO (%PPO) versus time (collapsed across intensity).

The main effect for intensity and post-hoc t-tests with a Bonferroni corrected alpha (p<0.017) indicated that the relative PO for the HR_L (41.23±3.10%PPO) was significantly lower than the relative PO for HR_M (50.28±4.21%PPO, p<0.001) and HR_H (62.63±3.95%PPO, p<0.001). In addition, the relative PO for the HR_M trial was significantly (p<0.001) lower than the HR_H trial.

4.3.4 Metabolic Efficiency

A 2(Time; Start, End) x 3(Intensity; HR_L, HR_M, HR_H) repeated measures ANOVA to examine changes in the metabolic efficiency ($\dot{V}O_2$/PO) indicated there was no two-way interaction (F=2.119, p=0.144, η_p^2=0.162). There was, however, main effects for time (F= 46.001, p<0.001, η_p^2=0.807), but not intensity (F=2.151, p=0.140, η_p^2=0.164). The main effect for time and post-hoc t-tests indicated that $\dot{V}O_2$/PO ratio was lower at the start (10%T_{lim}) compared to the end (100% T_{lim}), collapsed across intensity (p<0.001) (Table 13).

4.3.4 Respiratory Exchange Ratio (RER)

A 3 (Intensity; HR_L, HR_M, HR_H) x 10(Time; %T_{Lim} [10-100]) repeated measures ANOVA to examine changes in RER indicated there was an intensity x time interaction (F=9.808, p<0.001, η_p^2=0.471). The follow up one way ANOVA for each of the three intensities (HR_L, F=12.966, p<0.001, η_p^2=0.541; HR_M, F=42.204, p<0.001, η_p^2=0.793; HR_H, F=57.892, p<0.001, η_p^2=0.840) and post-hoc t-tests, with a Bonferroni indicated that the RER at HR_L, was significantly lower than the initial value (10%) from 20-100% of T_{lim}

(p=0.0001 to 0.0006). The RER at HR_M was also significantly lower than the initial value (10%) from 20-100% of T_{lim} (p<0.001 for all comparisons). In addition, the RER at HR_H was significantly lower than the initial value (10%) from 20-100% of T_{lim} (p<0.001 for all comparisons) (Figure 4). The results of the polynomial regression analyses indicated that there were negative, quadratic relationships for RER ($\%RER_{peak}$) versus time for HRL (R^2=0.931), HRM (R^2=0.898), and HRH (R^2=0.910). The results of the 10 separate follow-up 1 (time) x 3(Intensity; HR_L, HR_M, HR_H) repeated measures ANOVAs and post-hoc t-tests with a Bonferroni corrected alpha (p<0.017) are indicated in the table 13.

4.3.5 Minute Ventilation ($\dot{V}_E$)

A 3 (Intensity; HR_L, HR_M, HR_H) x 10(Time; $\%T_{Lim}$ [10-100]) repeated measures ANOVA to examine changes in $\dot{V}_E$ indicated there was no two-way interaction (F=1.841, p=0.173, η_p^2=0.143, Greenhouse-Geisser correction). There were, however, main effects for intensity (F=85.693, p<0.001, η_p^2=0.886) and time (F= 20.857, p<0.001, η_p^2=0.655). The main effect for time and post-hoc t-tests with a Bonferroni corrected alpha (p<0.005) indicated that $\dot{V}_E$, collapsed across intensity, was significantly lower than the initial value (10%) from 20-100% of T_{lim} (p=0.0001 to 0.0002) (Figure 5). The results of the polynomial regression analyses indicated that there was a negative, quadratic relationship (R^2=0.949) for $\dot{V}_E$ ($\%\dot{V}_{Epeak}$) versus time (collapsed across intensity).

The main effect for intensity and post-hoc t-tests with a Bonferroni corrected alpha (p<0.017) indicated that the relative $\dot{V}_E$ for the HR_L (39.13±1.39$\%\dot{V}_{Epeak}$) was significantly lower than the relative $\dot{V}_E$ for HR_M (49.12±2.73$\%\dot{V}_{Epeak}$, p<0.001) and HR_H

(71.66±3.42%$\dot{V}_{Epeak}$, p<0.001). In addition, the relative $\dot{V}_E$ for the HR_M trial was significantly (p<0.001) lower than the HR_H trial.

4.3.6 Respiratory Rate (RR)

A 3 (Intensity; HR_L, HR_M, HR_H) x 10(Time Course; %T_{lim} [10-100]) repeated measures ANOVA to examine changes in RR indicated there was no two-way interaction (F=1.955, p=0.141, η_p^2=0.151, Greenhouse-Geisser correction). There were, however, main effects for intensity (F=53.017, p <0.001, η_p^2=0.828) and time (F= 10.795, p <0.001, η_p^2=0.495). The main effect for time and post-hoc t-tests with a Bonferroni corrected alpha (p<0.005) indicated that RR, collapsed across intensity, was significantly higher than the initial value (10%) from 70-90% of T_{lim} (p=0.0013 to 0.0019) (Figure 6). The results of the polynomial regression analyses indicated that there was a positive, quadratic relationship (R^2=0.996) for RR (%RR_{peak}) versus time (collapsed across intensity).

The main effect for intensity and post-hoc t-tests with a Bonferroni corrected alpha (p<0.017) indicated that the relative RR for the HR_L (58.60±1.69%RR) was significantly lower than the relative RR for HR_M (67.18±2.63% RR_{peak}, p=0.010) and HR_H (86.27±4.17%RR_{peak}, p <0.001). In addition, the relative RR for the HR_M trial was significantly (p<0.001) lower than the HR_H trial.

4.4 Constant Heart Rate Trials: Time in Intensity Domains (Aim 3)

During the HR_L (77%HR_{peak}) trial, the participants reached the selected HR within 0.00-3.34 min (2.11±0.99 min) and the T_{lim} was 53.72±13.36 min (Table 4). During the HR_M (86%HR_{peak}) trial, the participants reached the selected HR within 0.67-3.66 min (2.53±0.96 min) and the T_{lim} was 46.75±18.79 min (Table 5). During the HR_H (95%HR_{peak})

trial, the participants reached the selected HR within 2.00-4.34 min (3.03±0.74 min) and the T_{lim} was 27.08±18.06 min (Table 6).

The results of the 3 (intensity: HR_L, HR_M, HR_H) x 3 (domain: moderate, heavy, severe) repeated measures ANOVA examining time in each intensity domain indicated there was a 2-way interaction ($F = 25.588$, $p \leq 0.001$, $\eta_p^2 = 0.699$). Therefore, separate, 1 (intensity) x 3 (domain: moderate, heavy, severe) repeated measures ANOVAs and post-hoc t-tests with a Bonferroni corrected alpha (< 0.017) were used to examine time in each domain for HR_L, HR_M, HR_H. In addition, separate, 1(domain) x 3(intensity: HR_L, HR_M, HR_H) repeated measures ANOVAs and post-hoc t-tests with a Bonferroni corrected alpha ($p < 0.017$) were used to compare the time spent in the moderate, heavy, and severe domains.

4.4.1 HR_L Trial

The follow-up 1(intensity) x 3(domain: moderate, heavy, severe) repeated measures ANOVA for the HR_L trial indicated there were significant ($F = 108.9$, $p < 0.001$, $\eta_p^2 = 0.908$) differences in the time spent in each domain. The post-hoc t-tests indicated that participants (mean± SD) spent significantly more time in the moderate domain (53.50±15.57 min) than the heavy (2.33±3.74 min, $p \leq 0.001$) and severe (0.00±0.00, $p \leq 0.001$). There was no significant difference in the time spent within the heavy and severe domains ($p = 0.053$).

4.4.2 HR_M Trial

The follow-up 1(intensity) x 3(domain: moderate, heavy, severe) repeated measures ANOVA for the HR_M trial indicated there were significant ($F = 30.092$, $p < 0.001$, $\eta_p^2 = 0.732$) differences in the time spent in each domain. The post-hoc t-tests indicated that participants (mean± SD) spent significantly more time in the moderate domain (43.58±23.07 min) than the heavy (5.67±5.27 min, $p = 0.002$) and severe (0.17±0.48, $p \leq 0.001$) min. In addition, the participants spent significantly more time in the heavy than severe domain (p=0.010).

4.4.3 HR_H Trial

The follow-up 1(intensity) x 3(domain: moderate, heavy, severe) repeated measures ANOVA for the HR_H trial indicated there were significant ($F = 4.070$, $p = 0.031$, $\eta_p^2 = 0.270$) differences in the time spent in each domain. The post-hoc t-tests indicated that participants (mean± SD) there was no significant difference in the time spent in the moderate domain (17.81±18.40 min) and heavy (10.53±12.11 min, $p = 0.318$) and moderate or severe (1.78±1.98, $p = 0.017$) min. There was no significant difference in the time spent within the heavy and severe ($p = 0.036$).

4.4.4 Moderate

The follow-up 1(domain) x 3(intensity: HR_L, HR_M, HR_H) repeated measures ANOVA for the moderate domain indicated there were significant ($F = 36.473$, $p < 0.001$, η_p^2 participants (mean± SD) spent significantly more time in the moderate domain for HR_L (53.50±15.57 min) than the HR_M, (43.58±23.07 min, $p = 0.014$) and HR_H (17.81±18.40 min, $p \leq 0.001$). In addition, the participants spent significantly more time in the HR_M than the HR_H intensity ($p \leq 0.001$)

4.4.4 Heavy

The follow-up 1(domain) x 3(intensity: HR_L, HR_M, HR_H) repeated measures ANOVA for the heavy domain indicated there were no significant ($F = 3.663$, $p=0.078$, $\eta_p^2 =0.250$) differences in the time spent in each intensity. The post-hoc t-tests indicated that participants (mean± SD) spent significantly more time in the heavy domain for HR_M (5.67±5.27 min) than the HR_L, (2.33±3.74 min, $p \leq 0.001$). However, there was no significant difference in the time spent in HR_H (10.53±12.11 min) than the HR_M, (5.67±5.27 min, $p =0.199$) or HR_L (2.33±3.74 min, $p =0.054$) in the heavy domain.

4.4.5 Severe

The follow-up 1(domain) x 3(intensity: HR_L, HR_M, HR_H) repeated measures ANOVA for the severe domain indicated there were significant ($F = 8.979$, $p=0.010$, $\eta_p^2 =0.449$) differences in the time spent in each intensity. The post-hoc t-tests indicated that participants (mean± SD) spent significantly more time in the severe domain for HR_H (1.78±1.98) than the HR_M, (0.17±0.48 min, $p =0.013$) or HR_L (0.00±0.00min, $p =0.009$). There was no significance difference in the time spent in the severe domain for HR_M and HR_L ($p=0.257$).

Table 1. Descriptive characteristics of the participants and their corresponding age predicted maximum heart rate (APMHR).

Participants	Age(years)	Height(cm)	Weight (kg)	APMHR (beats·min^{-1})
1	30	181.4	78.6	186
2	23	166.0	74.2	191
3	24	160.7	55.0	190
4	22	167.2	74.7	192
5	21	162.5	67.5	192
6	21	176.0	61.5	192
7	21	158.0	66.4	192
8	21	172.8	60.7	192
9	21	171.1	59.5	192
10	33	173.0	72.1	184
11	23	182.2	104.0	191
12	21	167.8	62.0	192
Mean	**23**	**169.9**	**69.7**	**191**
SD	**4**	**7.3**	**13.0**	**3**

Note: APMHR was calculated using the equation 207x0.7-age.

Table 2. Individual and mean ± SD responses for the metabolic, ventilatory, perceptual, and power output variables recorded during the graded exercise test to exhaustion. Peak oxygen consumption ($\dot{V}O_{2peak}$), peak of heart rate (HR_{peak}), peak respiration rate (RR_{peak}), peak rate of perceived exertion (RPE_{peak}), peak respiratory exchange ratio (RER_{peak}), peak ventilation ($\dot{V}_{Epeak}$), and time to exhaustion (T_{lim}).

Participant	$\dot{V}O_{2peak}$ (ml·kg^{-1}·min^{-1})	HR_{peak} (beats·min^{-1})	RRpeak (breaths·min^{-1})	Peak Power (W)	RPEpeak	RER_{peak}	$\dot{V}_{Epeak}$	T_{lim} (min)
1	40.26	186	60.76	260	19	1.24	141.61	16.18
2	45.88	188	53.46	260	18	1.24	129.65	16.32
3	39.42	184	56.16	200	19	1.23	97.41	11.64
4	24.19	195	53.63	170	17	1.16	64.92	9.65
5	34.07	178	40.35	200	19	1.13	83.13	11.18
6	24.82	178	46.27	140	17	1.28	63.19	7.99
7	41.75	198	52.52	259	20	1.18	109.63	14.64
8	41.88	193	49.05	230	20	1.16	92.62	12.98
9	34.51	191	44.25	170	20	1.19	80.47	10.01
10	38.73	165	44.73	200	20	1.26	108.11	11.95
11	32.71	177	44.14	260	18	1.09	122.68	15.31
12	34.21	189	61.41	198	18	1.18	99.52	10.32
Mean	**36.04**	**185**	**51.56**	**212.00**	**19.00**	**1.20**	**99.00**	**12.35**
SD	**7.23**	**9.33**	**6.84**	**41.32**	**1.14**	**0.06**	**24.88**	**2.74**

Table 3. Individual and mean ± SD data for the thresholds derived from the graded exercise test expressed relative to body weight (ml·kg^{-1} ·min^{-1}) and as a percentage of the respective peak value.

Participant	VT (ml·kg^{-1} ·min^{-1})	RCP (ml·kg^{-1} ·min^{-1})	PO VT (W)	PO RCP (W)	VT % $\dot{V}O_{2peak}$	RCP % $\dot{V}O_{2peak}$	VT %PPO	RCP %PPO
1	22.27	32.19	145	219	55	80	56	84
2	23.28	35.74	133	224	51	78	71	86
3	27.53	34.35	133	175	70	87	73	87
4	16.37	19.85	98	131	68	82	50	77
5	20.31	25.42	109	143	60	75	61	72
6	18.65	22.73	93	128	75	92	52	91
7	26.86	37.46	148	222	64	90	75	86
8	31.79	39.00	167	213	76	93	86	92
9	22.72	29.82	108	154	66	86	57	90
10	22.35	28.14	129	166	58	73	78	83
11	18.28	24.77	142	204	56	76	80	79
12	23.00	29.44	117	158	67	86	62	80
Mean	**22.78**	**29.91**	**128**	**181**	**64**	**83**	**67**	**84**
SD	**4.32**	**6.04**	**21**	**33**	**8**	**7**	**12**	**6**

Ventilatory threshold (VT), respiratory compensation point (RCP), power output at the VT (PO VT), power output at the RCP (PO RCP).

Table 4. Individual and mean ± SD responses for the time to reach the required heart rate (HR) and time to exhaustion at the required HR for the lower HR (HR_L=77%HR_{peak}) trials.The average HR, $\dot{V}O_2$, power output, and rating of perceived exertion for the whole constant HR trial, expressed relative to its respective peak value.

Participant	Time to Threshold (min)	Time to Exhaustion (min)	Average HR (beats·min^{-1})	% $\dot{V}O_{2peak}$	%PPO	RPE	%RPE_{peak}
1	3.34	25.33	144	63	53	17	90
2	2.33	60.00	145	42	31	11	61
3	2.00	60.00	142	57	45	11	56
4	0.00	60.00	150	59	37	8	49
5	3.00	26.67	137	60	45	13	70
6	2.00	60.00	137	60	41	10	57
7	2.34	60.00	152	58	42	14	71
8	1.00	60.00	149	42	29	8	41
9	2.67	60.00	147	50	39	13	65
10	2.67	60.00	127	49	48	15	77
11	3.00	49.00	137	56	51	10	53
12	1.00	60.00	146	51	34	10	56
Average	**2.99**	**53.42**	**143**	**54**	**41**	**12**	**62**
SD	**0.99**	**13.19**	**8**	**7**	**8**	**3**	**13**

% $\dot{V}O_{2peak}$ = average oxygen consumption relative to peak, %PPO = average power output relative to peak power output, RPE= average absolute rating of perceived exertion, %RPE_{peak} = average rating of perceived exertion relative to peak.

Note: The time to exhaustion includes only the time spent at the required heart rate

Table 5. Individual and mean ± SD responses for the time to reach the required heart rate (HR) and time to exhaustion at the required HR for the middle HR(HR_M=86%HR_{peak}) trials. The average HR, $\dot{V}O_2$, power output, and rating of perceived exertion for the whole constant HR trial, expressed relative to its respective peak value.

Participant	Time to Threshold (min)	Time to Exhaustion (min)	Average HR (beats·min^{-1})	% $\dot{V}O_{2peak}$	%PPO	RPE	%RPE_{peak}
1	3.66	13.67	161	75	63	17	92
2	3.33	60.00	164	54	45	12	65
3	2.67	60.00	158	70	56	14	73
4	0.67	60.00	168	68	43	16	92
5	2.00	24.33	153	68	54	15	80
6	1.67	47.33	153	72	54	14	81
7	3.33	60.00	170	66	48	15	75
8	2.33	60.00	166	59	46	13	66
9	3.00	60.00	164	50	37	14	70
10	2.67	39.67	142	61	59	16	80
11	3.66	15.33	152	63	58	12	68
12	1.33	60.00	163	59	42	15	83
Average	**2.53**	**46.75**	**159**	**64**	**50**	**14**	**77**
SD	**0.96**	**18.79**	**8**	**7**	**8**	**2**	**9**

% $\dot{V}O_{2peak}$ = average oxygen consumption relative to peak, %PPO = average power output relative to peak power output, RPE= average absolute rating of perceived exertion, %RPE_{peak} = average rating of perceived exertion relative to peak

Note: The time to exhaustion includes only the time spent at the required heart rate

Table 6. Individual and mean ± SD time to reach the required heart rate (HR) and time to exhaustion at the required HR for the higher HR (HR_H=95%HR_{peak}) trials and the average HR, $\dot{V}O_2$, power output, and rating of perceived exertion for the whole constant HR trial, expressed relative to its respective peak value.

Participant	Time to Threshold (min)	Time to Exhaustion (min)	Average HR (beats·min^{-1})	% $\dot{V}O_{2peak}$	%PPO	RPE	%RPE_{peak}
1	3.67	10.00	177	82	68	19	99
2	3.67	26.67	179	78	57	15	83
3	3.00	32.67	175	82	64	18	96
4	2.67	25.66	185	82	56	17	103
5	2.67	8.33	169	86	67	17	89
6	2.33	35.00	169	85	60	16	95
7	4.34	53.66	188	82	60	19	95
8	3.66	33.34	183	77	60	17	83
9	2.33	60.00	181	64	50	18	89
10	2.34	4.33	157	80	76	17	87
11	3.67	5.33	167	95	80	15	83
12	2.00	29.67	180	71	53	18	99
Average	**3.03**	**27.05**	**176**	**80**	**63**	**17**	**92**
SD	**0.74**	**18.00**	**9**	**8**	**9**	**1**	**7**

% $\dot{V}O_{2peak}$ = average oxygen consumption relative to peak, %PPO = average power output relative to peak power output, RPE= average absolute rating of perceived exertion, %RPE_{peak} = average rating of perceived exertion relative to peak

Note: The time to exhaustion includes only the time spent at the required heart rate

Table 7. Individual responses for relative volume oxygen consumption (%$\dot{V}O_{2peak}$) and time exhaustion (T_{lim}) at HR_L.

	Participant											
Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
10%	70	47	60	61	66	66	65	48	58	58	61	51
20%	71	45	58	60	61	61	60	41	54	53	58	51
30%	63	45	57	60	60	61	59	40	53	52	55	52
40%	66	43	57	59	60	59	60	39	50	49	53	52
50%	59	37	57	58	58	62	59	39	49	48	52	51
60%	63	35	56	59	59	60	58	40	48	47	52	51
70%	60	41	55	60	60	58	57	41	46	46	53	52
80%	60	42	55	59	59	58	55	42	46	47	54	51
90%	62	44	55	59	58	60	55	42	46	46	60	51
100%	56	44	56	59	57	59	54	43	44	47	60	51
Mean	**63**	**42**	**57**	**59**	**60**	**60**	**58**	**42**	**50**	**49**	**56**	**51**
SD	**5**	**4**	**2**	**1**	**2**	**2**	**3**	**3**	**4**	**4**	**3**	**1**
T_{lim}	**25.33**	**60.00**	**60.00**	**60.00**	**26.67**	**60.00**	**60.00**	**60.00**	**60.00**	**60.00**	**49.00**	**60.00**

Table 8. Individual responses for relative volume oxygen consumption (%$\dot{V}O_{2peak}$) and time exhaustion (T_{lim}) at HR_M.

	Participant											
Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
10%	86	57	76	74	74	79	78	71	62	73	74	65
20%	82	55	73	70	70	78	71	63	55	68	65	60
30%	77	56	71	69	68	74	69	61	52	66	64	59
40%	78	55	71	65	67	75	65	58	50	61	63	59
50%	77	54	70	65	69	72	64	57	49	59	65	58
60%	75	54	70	66	68	69	63	57	48	58	65	58
70%	72	53	69	67	67	68	62	57	46	57	60	58
80%	67	53	66	69	68	67	62	55	47	57	60	58
90%	69	53	67	70	65	68	63	57	48	56	58	57
100%	70	53	65	68	64	70	63	57	45	56	59	59
Mean	**75**	**54**	**70**	**68**	**68**	**72**	**66**	**59**	**50**	**61**	**63**	**59**
SD	**6**	**1**	**3**	**3**	**3**	**4**	**5**	**5**	**5**	**6**	**5**	**2**
T_{lim}	**13.67**	**60.00**	**60.00**	**60.00**	**24.33**	**47.33**	**60.00**	**60.00**	**60.00**	**39.67**	**15.33**	**60.00**

Table 9. Individual responses for relative volume oxygen consumption (%$\dot{V}O_{2peak}$) and time exhaustion (T_{lim}) at HR_H.

	Participant											
Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
10%	90	90	89	96	86	91	86	87	74	83	102	83
20%	90	82	87	92	89	89	88	81	66	81	98	75
30%	92	84	84	89	89	88	85	75	63	79	93	73
40%	89	76	82	86	87	88	82	77	63	80	92	71
50%	83	78	83	82	86	84	82	75	62	79	94	68
60%	76	74	83	80	88	83	80	76	62	75	98	69
70%	74	74	81	77	85	82	79	75	65	84	95	68
80%	74	75	79	76	82	82	80	74	62	81	94	69
90%	75	75	76	72	80	81	79	75	60	88	95	66
100%	79	71	80	71	84	81	78	74	62	73	92	66
Mean	**82**	**78**	**82**	**82**	**86**	**85**	**82**	**77**	**64**	**80**	**95**	**71**
SD	**8**	**6**	**4**	**9**	**3**	**4**	**3**	**4**	**4**	**4**	**3**	**5**
T_{lim}	**10.00**	**26.67**	**32.67**	**25.66**	**8.33**	**35.00**	**53.66**	**33.34**	**60.00**	**4.33**	**5.33**	**29.67**

Table 10. Individual responses for absolute rate of perceived exertion (RPE) and time exhaustion (T_{lim}) at HR_L.

	Participant											
Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
10%	14	10	9	7	12	8	12	7	12	14	7	8
20%	15	11	10	7	15	8	14	7	13	14	7	9
30%	15	12	10	7	15	9	14	7	13	15	7	9
40%	17	12	10	7	13	10	15	8	12	15	7	10
50%	17	10	10	7	10	11	14	8	13	15	7	10
60%	18	11	11	8	11	10	15	8	14	16	7	11
70%	18	11	11	9	12	9	15	8	13	16	9	11
80%	19	11	12	10	15	10	15	9	14	16	13	11
90%	20	11	12	11	16	11	15	9	13	16	14	12
100%	20	11	13	12	15	12	15	10	13	17	17	12
Mean	**17**	**11**	**11**	**8**	**13**	**10**	**14**	**8**	**13**	**15**	**10**	**10**
SD	**2**	**1**	**1**	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**4**	**1**
T_{lim}	**25.33**	**60.00**	**60.00**	**60.00**	**26.67**	**60.00**	**60.00**	**60.00**	**60.00**	**60.00**	**49.00**	**60.00**

Table 11. Individual responses for absolute rate of perceived exertion (RPE) and time exhaustion (T_{lim}) at HR_M.

	Participant											
Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
10%	15	11	13	12	13	11	13	12	12	14	10	12
20%	16	12	13	13	13	13	14	13	12	15	10	14
30%	15	12	13	14	13	13	15	13	12	15	12	14
40%	17	12	13	13	14	12	16	13	13	15	10	15
50%	17	12	14	14	15	14	16	13	14	15	12	15
60%	17	11	14	16	16	14	16	13	15	16	12	15
70%	19	12	14	18	17	12	16	14	15	17	13	15
80%	19	12	14	19	17	14	14	13	15	17	14	16
90%	20	12	15	19	17	17	15	14	16	17	15	17
100%	20	11	15	20	18	18	15	14	16	18	15	17
Mean	**17**	**12**	**14**	**16**	**15**	**14**	**15**	**13**	**14**	**16**	**12**	**15**
SD	**2**	**0**	**1**	**3**	**2**	**2**	**1**	**1**	**2**	**1**	**2**	**2**
T_{lim}	**13.67**	**60.00**	**60.00**	**60.00**	**24.33**	**47.33**	**60.00**	**60.00**	**60.00**	**39.67**	**15.33**	**60.00**

Table 12. Individual responses for absolute rate of perceived exertion (RPE) and time exhaustion (T_{lim}) at HR_H.

	Participant											
Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
10%	16	13	16	14	16	15	16	16	15	15	13	16
20%	17	13	17	15	17	13	18	14	15	17	14	17
30%	19	15	17	16	18	15	19	13	16	17	14	17
40%	19	15	17	16	18	17	19	15	17	17	15	17
50%	20	15	18	18	19	18	20	16	18	17	15	17
60%	20	15	19	17	17	17	20	17	19	17	15	18
70%	19	15	19	19	17	15	20	18	19	18	15	19
80%	19	15	20	19	16	14	20	18	19	18	16	19
90%	20	16	20	20	16	18	19	19	20	18	16	19
100%	20	17	20	20	15	20	20	20	19	20	17	19
Mean	**19**	**15**	**18**	**17**	**17**	**16**	**19**	**17**	**18**	**17**	**15**	**18**
SD	**1**	**1**	**1**	**2**	**1**	**2**	**1**	**2**	**2**	**1**	**1**	**1**
T_{lim}	**10.00**	**26.67**	**32.67**	**25.66**	**8.33**	**35.00**	**53.66**	**33.34**	**60.00**	**4.33**	**5.33**	**29.67**

Table 13. Individual and mean±SD of the average heart rate (HR) during the trial in the lower HR(HR_L=77%HR_{peak}), middle HR(HR_M=86%HR_{peak}), and higher HR(HR_H=95%HR_{peak}), the metabolic efficiency($\dot{V}O_2$/PO) at the start and end of each trial, collapsed across intensity.

Participant	HR_L $\dot{V}O_2$/PO Start	HR_L $\dot{V}O_2$/PO End	HR_M $\dot{V}O_2$/PO Start	HR_M $\dot{V}O_2$/PO End	HR_H $\dot{V}O_2$/PO Start	HR_H $\dot{V}O_2$/PO End	Collapsed $\dot{V}O_2$/PO Start	Collapsed $\dot{V}O_2$/PO End
1	0.16	0.20	0.17	0.18	0.17	0.18	0.17	0.19
2	0.21	0.25	0.20	0.23	0.22	0.25	0.21	0.24
3	0.24	0.26	0.24	0.26	0.25	0.26	0.25	0.26
4	0.21	0.24	0.21	0.23	0.20	0.23	0.20	0.23
5	0.22	0.24	0.21	0.22	0.20	0.22	0.21	0.23
6	0.25	0.27	0.23	0.25	0.24	0.26	0.24	0.26
7	0.22	0.22	0.22	0.23	0.22	0.22	0.22	0.23
8	0.25	0.25	0.22	0.25	0.23	0.23	0.24	0.24
9	0.24	0.28	0.26	0.30	0.25	0.26	0.25	0.28
10	0.19	0.21	0.21	0.20	0.17	0.20	0.19	0.20
11	0.13	0.15	0.13	0.14	0.15	0.15	0.14	0.15
12	0.25	0.26	0.23	0.26	0.23	0.23	0.24	0.25
Average	**0.21**	**0.24**	**0.21**	**0.23**	**0.21**	**0.22**	**0.21**	**0.23**
SD	**0.04**	**0.03**	**0.03**	**0.04**	**0.03**	**0.03**	**0.03**	**0.03**

$\dot{V}O_2$/PO Start= determined from the $\dot{V}O_2$ measured at the start of the trial/ power output ratio

$\dot{V}O_2$/PO End=determined from the $\dot{V}O_2$ measured at the end of the trial/ power output ratio

Table 14. Repeated-measures ANOVA results, One-way ANOVA, and post-hoc results with a Bonferroni Corrected alpha $p<0.017$ here for the change in RER intensities across time.

	Respiratory Exchange Ratio (%)			Follow up one-way ANOVA			Post Hoc comparison		
Time	HR_L	HR_M	HR_H	F value	Sig.	Effect size η_P^2	HR HR_L and HR_M	HR HR_L and HR_H	HR HR_M and HR_H
10%	80.983±4.471	83.761±4.905	93.544±6.173	34.267	<0.001	0.757	0.045	<0.001*	<0.001*
20%	78.479±4.405	79.762±5.228	86.477±6.312	15.935	<0.001	0.592	0.311	<0.001*	0.004*
30%	77.493±4.483	78.045±4.302	84.463±6.017	14.150	<0.001	0.563	0.703	<0.001*	0.002*
40%	77.951±4.676	77.703±4.941	83.480±5.835	10.439	<0.001	0.487	0.878	<0.001*	0.003*
50%	76.897±4.543	76.593±4.736	82.803±5.129	11.363	<0.001	0.508	0.856	<0.001*	0.001*
60%	76.020±4.467	76.563±5.328	81.574±5.428	9.015	0.001	0.450	0.741	<0.001*	0.006*
70%	75.679±4.598	76.525±5.516	81.413±5.290	8.316	0.002	0.431	0.587	0.002*	0.010*
80%	75.629±5.246	76.534±5.164	80.531±4.838	6.411	0.006	0.368	0.557	0.007*	0.016*
90%	75.745±5.634	75.574±4.874	80.309±4.689	6.755	0.005	0.380	0.913	0.015*	0.003*
100%	75.481±5.805	75.573±4.268	79.807±4.204	5.791	0.10	0.345	0.952	0.019	0.007*

*Indicates a significant difference in RER between the 3 intensities (p<0.017)

Table 15. Individual and mean ± SD responses for the time spent in the moderate, heavy and, severe intensity domain during each constant heart rate trial.

	Moderate			Heavy			Severe		
Participant	HR_L (min)	HR_M (min)	HR_H (min)	HR_L (min)	HR_M (min)	HR_H (min)	HR_L (min)	HR_M (min)	HR_H (min)
1	18.67	3.00	0.33	10.00	14.33	10.00	0.00	0.00	3.33
2	62.33	54.00	7.67	1.67	9.33	20.33	0.00	0.00	2.33
3	62.33	61.33	23.67	0.00	1.67	12.00	0.00	0.00	0.00
4	60.33	60.00	16.33	0.00	1.00	9.33	0.00	0.00	2.67
5	26.67	15.33	0.00	3.00	9.33	8.33	0.00	1.67	2.67
6	62.00	49.00	34.00	0.00	0.00	3.33	0.00	0.00	0.00
7	62.00	56.67	12.67	0.67	7.00	45.33	0.00	0.00	0.00
8	61.33	63.00	33.33	0.00	0.00	3.67	0.00	0.00	0.00
9	63.00	61.67	59.33	0.00	1.67	3.33	0.00	0.00	0.00
10	60.33	32.67	0.00	2.67	9.67	3.67	0.00	0.00	3.00
11	42.00	6.00	0.00	10.00	12.67	2.67	0.00	0.33	6.33
12	61.00	60.33	26.33	0.00	1.33	4.33	0.00	0.00	1.00
Average	**53.50**	**43.58**	**17.81**	**2.33**	**5.67**	**10.53**	**0.00**	**0.17**	**1.78**
SD	**15.57**	**23.07**	**18.40**	**3.74**	**5.27**	**12.11**	**0.00**	**0.48**	**1.98**

Below ventilatory threshold (VT)= moderate intensity domain. Lower Heart Rate trial (HR_L=77%HR_{peak}). Middle Heart Rate trial (HR_M=86%HR_{peak}). Higher Heart Rate trial (HR_H=95%HR_{peak})

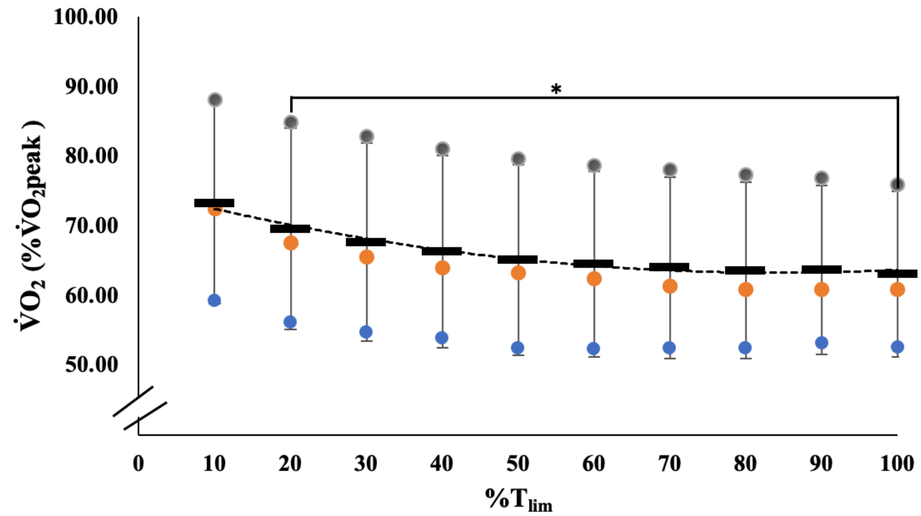

Figure.1 The time course of changes in the normalized $\dot{V}O_2$ values (%$\dot{V}O_{2peak}$) during the vigorous HR trials. The solid black bars and dotted line reflects the main effect for time, collapsed across HR_L, HR_M, HR_H. * Indicates a significant decrease when compared to the initial value.

Note: Blue, orange, and grey data points reflect the responses for the HR_L, HR_M, and HR_H trials, respectively, and are provided for visualization of the data

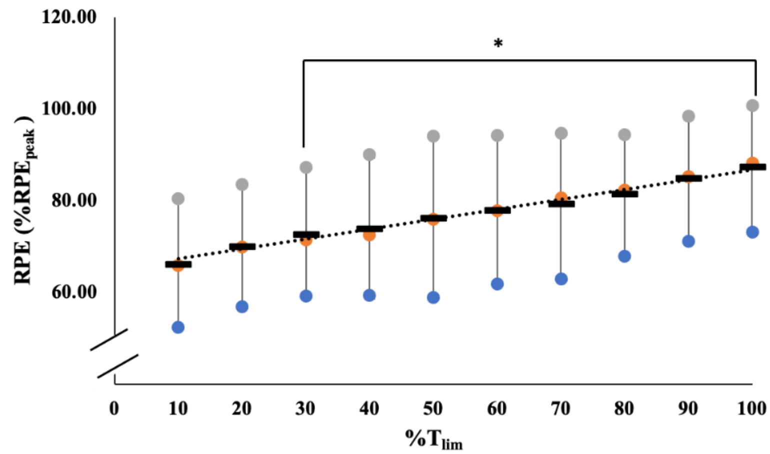

Figure 2. The time course of changes in the normalized RPE values (%RPE$_{peak}$) during the vigorous HR trials. The solid black bars and dotted line reflects the main effect for time, collapsed across HR$_L$, HR$_M$, HR$_H$. * Indicates a significant decrease when compared to the initial value. Note: Blue, orange, and grey data points reflect the responses for the HR$_L$, HR$_M$, and HR$_H$ trials, respectively, and are provided for visualization of the data.

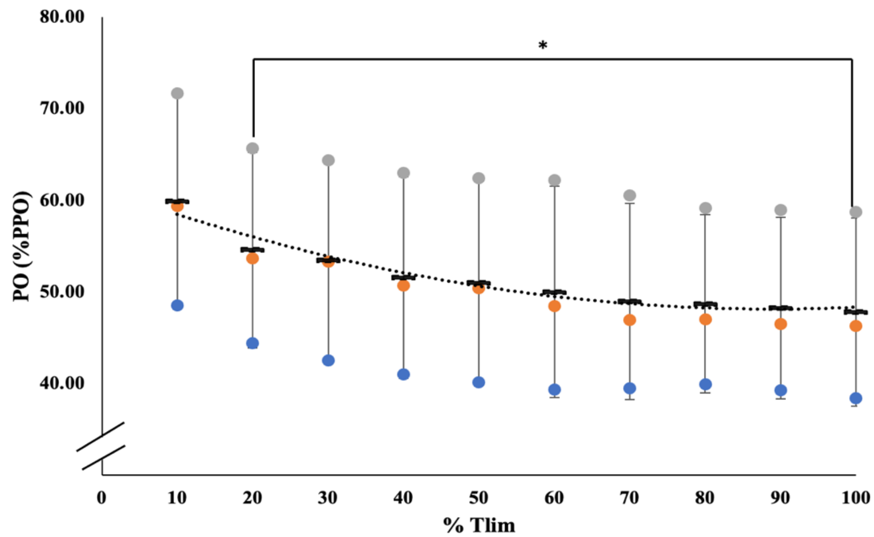

Figure 3. The time course of changes in the normalized power output (PO) values (%PPO) during the vigorous HR trials. The solid black bars and dotted line reflects the main effect for time, collapsed across HR_L, HR_M, HR_H. * Indicates a significant decrease when compared to the initial value.

Note: Blue, orange, and grey data points reflect the responses for the HR_L, HR_M, and HR_H trials, respectively, and are provided for visualization of the data.

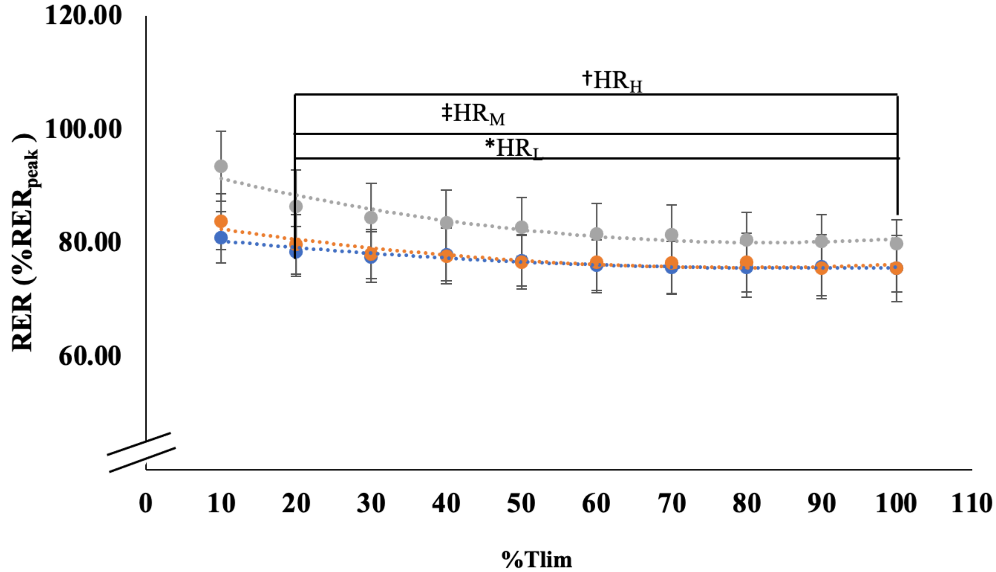

Figure 4. The time course of changes in the normalized respiratory exchange ratio (RER) values (%RER_{peak}) during the vigorous HR trials. The Blue, orange, and grey reflects the main effect for time at HR_L, HR_M, HR_H respectively. †‡* Indicates a significant decrease when compared to the initial value.

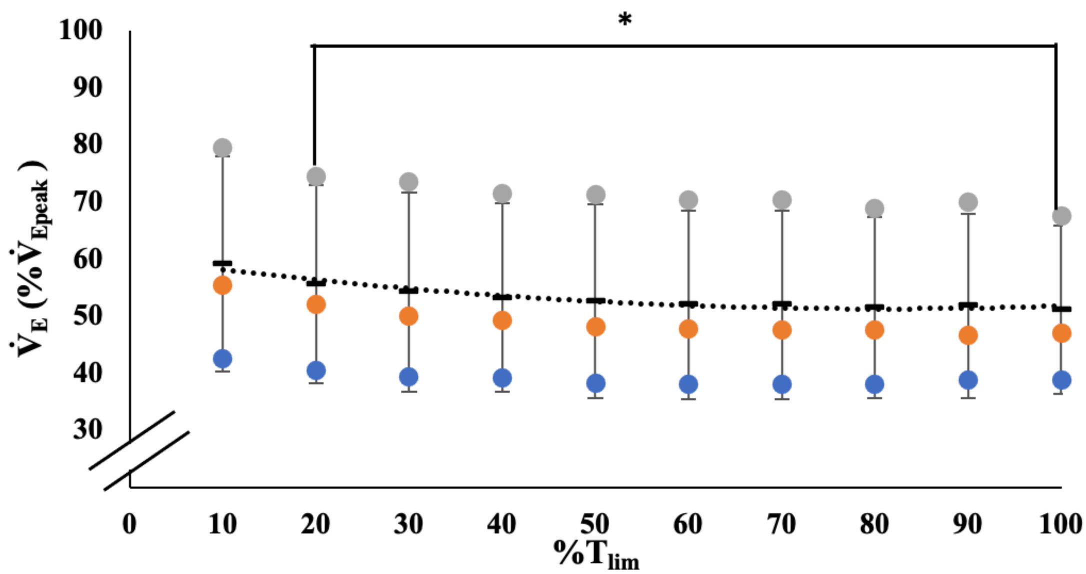

Figure 5. The time course of changes in the normalized $\dot{V}_E$ values (%$\dot{V}_{Epeak}$) during the vigorous HR trials. The solid black bars and dotted line reflects the main effect for time, collapsed across HR_L, HR_M, HR_H. * Indicates a significant decrease when compared to the initial value. Note: Blue, orange, and grey data points reflect the responses for the HR_L, HR_M, and HR_H trials, respectively, and are provided for visualization of the data.

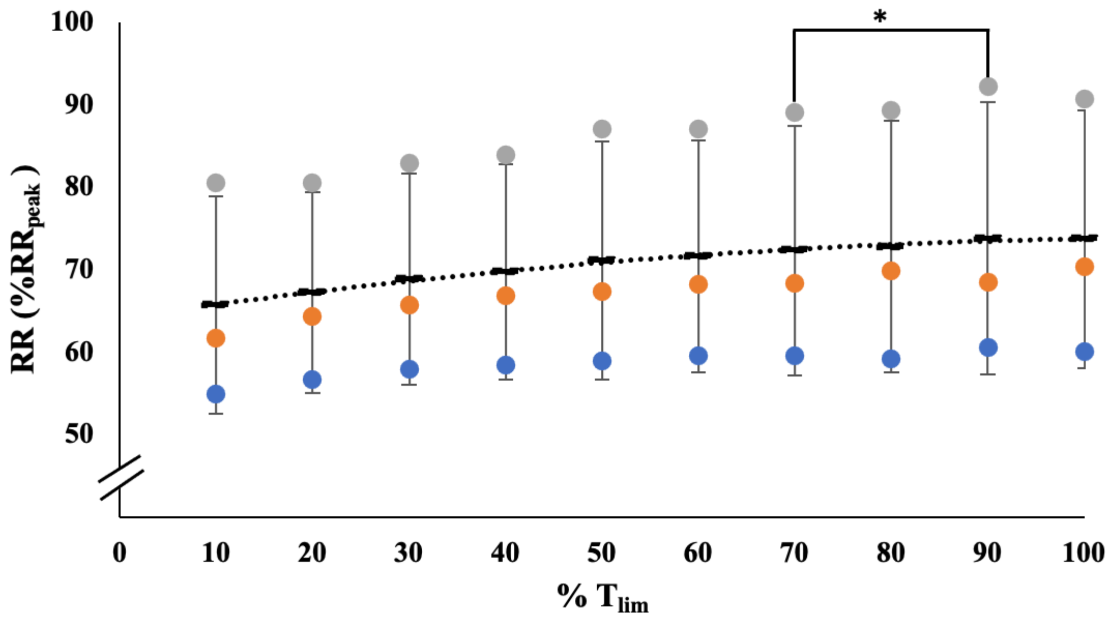

Figure 6. The time course of changes in the normalized respiratory rate (RR) values (%RR_{peak}) during the vigorous HR trials. The solid black bars and dotted line reflects the main effect for time, collapsed across HR_L, HR_M, HR_H. * Indicates a significant decrease when compared to the initial value.

Note: Blue, orange, and grey data points reflect the responses for the HR_L, HR_M, and HR_H trials, respectively, and are provided for visualization of the data

CHAPTER 5. DISCUSSION

The current ACSM guidelines recommend that exercise to improve CE be performed at vigorous exercise intensities that are based on a percentage of $\dot{V}O_{2max}$ or HR_{max} or the corresponding RPE. For the current study, percentages of HR_{peak} derived from a maximal effort GXT were used to examine these guidelines for cycle ergometry. This methodology was consistent with the ACSM guidelines recommendation that the HR to be used for exercise prescription be determined from a maximal effort test. The highest HR reached during the GXT was defined as the HR_{peak}. Therefore, the term peak was used throughout this manuscript to define the highest value for all variables ($\dot{V}O_{2peak}$, RPE_{peak}, PPO, RER_{peak}, $\dot{V}_{Epeak}$, RR_{peak}), in addition to HR_{peak}. In this study, the average HR_{peak} from the GXT was 185±9 $b \cdot min^{-1}$. The exercise prescription guidelines were then examined by anchoring exercise at a HR in the lower (HR_L=77%HR_{peak}), middle (HR_M=86%HR_{peak}), and higher (HR_H=95%HR_{peak}) end of the recommended range for vigorous cycle ergometry (77-95%HR_{peak}). This resulted in an average HR of 143±8 $b \cdot min^{-1}$, 159±8 $b \cdot min^{-1}$, and 176±9 $b \cdot min^{-1}$, for the HR_L, HR_M, and HR_H trials, respectively. If a GXT was not performed, the recommendation (Liguori et al.2020) is to use the age predicted HR maximum (or peak). Previous authors (Gellish et al.2007) have suggested that the equation, 207-0.7 x age, is more accurate than other age prediction equations for estimating HR_{peak}. Therefore, if we had used this equation to estimate HR_{peak}, rather than measure it from the GXT, the average estimated HR_{peak} would have been 191±3 $b \cdot min^{-1}$, which is 6 $b \cdot min^{-1}$ greater than the actual value obtained from the GXT (185±9.33 $b \cdot min^{-1}$). The constant HR trials in this study were maintained with ±2 $b \cdot min^{-1}$. Thus, it is likely that the 6 $b \cdot min^{-1}$ difference between estimated and measured HR_{peak} would have reflected different physiological responses and highlight one area of variability examining and applying the current exercise guidelines.

5.1 Metabolic and Perceptual Responses for HR_L

According to the ACSM guidelines, 77-95%HR_{peak} or an RPE between 14 and 17 will correspond to 64-90% $\dot{V}O_{2peak}$ for vigorous intensity exercise, and the exercise at this intensity should be sustained for 20-60 min to elicit improvements in CE. It is important to note that the intension of the HR and RPE ranges for vigorous exercise is to elicit the desired metabolic (64-90% $\dot{V}O_{2peak}$) demand for at least 20 min. At the HR_L (143±8 $b \cdot min^{-1}$) in this study, the participants sustained exercise for 53.42±13.19 min with an average RPE of 12±3, and the relative metabolic cost for the entire work bout was 53.9±7.1% $\dot{V}O_{2peak}$. Nine of the 12 participants were able to sustain the HR_L for 60 min, and all of the participants sustained the HR_L trial for at least 20 min (Table 4). On average the HR_L reflected a relative metabolic rate (%$\dot{V}O_{2peak}$) that was less than the recommended range for vigorous exercise throughout the trial (Figure 1). On a participant-by-participant basis, only 3 of the 12 participants were within the recommended $\dot{V}O_2$ range at the start of exercise (~10% of T_{lim}) before their responses fell below the lower end of the range. None of the participants were within the recommended range for $\dot{V}O_2$ ($\dot{V}O_2$ was less than 64% $\dot{V}O_{2peak}$) for at least 20 min of the HR_L trial (Table 7). For the RPE response at HR_L, 1 of the 12 participants was within the recommended range for less than 20 min before exceeding the upper limit (RPE >17), 2 of the 12 participants were within the recommended range for more than 20 min (RPE 14-17), 3 of the 12 participants were within the recommended range for less than 20 min, and 6 of the 12 participants never reached (RPE< 14) the desired perceptual response (Table 10). Thus, on average, the HR_L was sustained for the recommended duration but did not elicit a perceptual response or metabolic cost within the recommended range for most participants. Therefore, HR_L represented a sustainable intensity for all participants, but it may be a metabolic intensity that is too low to elicit desired improvement in CE fitness.

5.2 Metabolic and Perceptual Responses for HR_M

For the HR_M trial (159±8 $b \cdot min^{-1}$), the participants sustained exercise for 46.75±18.79 min at an RPE of 14±2, and with an average metabolic cost of 64±7% $\dot{V}O_{2peak}$ for the entire trial. Ten of the 12 participants sustained HR_M for at least 20 min and 7 of those participants were able to sustain HR_M for 60 min. However, 2 of the 12 participants were not able to sustain HR_M for at least 20 min (Table 5). Although the average $\dot{V}O_2$ for HR_M trial as a whole was within the recommended range, the time course of change responses (Figure 1) indicated HR_M reflected a % $\dot{V}O_{2peak}$ that was within the recommended range for a vigorous intensity for less than half of T_{lim}. Specifically, the average $\dot{V}O_2$ (63.9±3.73% $\dot{V}O_{2peak}$) fell below the recommended range at 40% of T_{lim}, which reflect 18.7 min of exercise and continued to decrease throughout the rest of trial (Figure 1). On a participant-by-participant basis 5 of the 12 participants were in the recommended $\dot{V}O_2$ range for more than 20 min and 5 of the 12 participants were within the range for less than 20 min. In addition, 2 of the 12 participants never reached the recommended range (Table 8). For the RPE at HR_M, 5 of the 12 participants were within the recommended range for at least 20 min, 6 participants were within the recommended range for less than 20 min, and 1 of the participants never reached the recommended range (Table 11). Thus, on average the HR_M trial elicited a metabolic intensity (64%$\dot{V}O_2$peak) and duration (at least 20 min) at or near the lowest end of the desired range for the composite, however, the individual responses indicated less than half (5 out of 12) participants were within the recommended $\dot{V}O_2$ and RPE range for at least 20 min. Thus, the metabolic responses at HR_M may be high enough to elicit the improvements in CE fitness for some, but HR_M did not reflect the desired metabolic response for the majority of participants.

5.3 Metabolic and Perceptual Responses for HR_H

For the HR For the HR_H trial (176±9 b·min^{-1}) the participants sustained exercise for 27.05±18 min at an RPE of 17±1, and with an average metabolic cost of 80±8% $\dot{V}O_{2peak}$ for the entire trial. Eight of the 12 participants were able to sustain that intensity for more than 20 min, but 4 participants only sustained that intensity for 10 min or less (Table 6). On average the HR_H reflected a % $\dot{V}O_{2peak}$ that was within the recommended range for vigorous intensity for the desired minimum duration. However, on a participant-by-participant basis, 7 of the 12 participants were in the recommended range for $\dot{V}O_2$ for at least 20 min. Four of the 12 participants were in the recommended range for less than 20 min and 1 of the participants exceeded the recommended range throughout the entire trial (Table 9). For the RPE at HR_H, 3 of the 12 participants were within the recommended range for at least 20 min, and 9 of the participants were within the recommended range for less than 20 min then exceeded it (Table 12). These findings indicated that the HR_H was at an intensity high enough to elicit an average metabolic intensity in the recommended range to elicit improvements in CE fitness for over half (58%) of the participant and could be sustained for at least 20 min for the majority (67%) of the participants. Thus, on average, the HR_H trial was within the recommendations for vigorous exercise. However, exercise prescription based on the HR_H should be made with caution as 33% of the participants were only able to sustain exercise at the required heart rate for 10 min or less (range 4.33 –10.00 min). Taken together, the responses HR_L, HR_M, and HR_H demonstrated that relative HR cannot be used to consistently prescribe exercise within the recommended metabolic range nor do these HR intensities consistently elicit a perceptual response described by the guidelines.

5.4 Time course of changes and patterns of responses

This study was the first to examine the patterns of physiological and perceptual responses during constant HR trials within the recommended range for vigorous intensity HR from the ACSM guidelines. Previous authors (Ribeiro et al. 1986, Stoudemire et al. 1996) have reported dissociations among the patterns of responses for metabolic and perceptual parameters for exercise at a constant physiological or perceptual parameter compared to constant work rate exercise. For example, Ribeiro et al. (1986) reported that when cycle ergometry exercise was held constant at approximately 54%$\dot{V}O_{2peak}$, there were decreases across time for PO and RER. In addition, Bergstrom et al. (2015b) examined responses to treadmill running anchored at the critical heart rate (CHR) which reflected 91% HR_{peak} and was sustained or ~48 min. The authors (Bergstrom et al. 2015b) reported decreases in $\dot{V}O_2$ from 88% to 76%$\dot{V}O_{2peak}$ (average of 16% decrease) and velocity was reduced by 23%. The results of the current study were consistent with this previous evidence and demonstrated that when exercise was anchored at a constant HR within the recommended vigorous range, there were decreases in $\dot{V}O_2$ that tracked and PO (Table 4,5,6). The composite $\dot{V}O_2$ responses, collapsed across HR intensity trial, indicated that these decreases were significantly lower than the initial value (10% T_{lim}) from 20-100%T_{lim} (Figure 1). The relative magnitude of these $\dot{V}O_2$ responses, however, were intensity dependent, such that, on average, $\dot{V}O_2$ decreased below the recommended metabolic intensity for HR_L and HR_M but stayed within the recommended range at HR_H. Specifically, during exercise at HR_L, the $\dot{V}O_2$ started at 59%$\dot{V}O_{2peak}$ and subsequently decreased following reduction of PO to 53%$\dot{V}O_{2peak}$ at T_{lim}. During exercise at HR_M, the $\dot{V}O_2$ started at 72%$\dot{V}O_{2peak}$ and subsequently decreased following reduction of PO to 61%$\dot{V}O_{2peak}$ at T_{lim}. During exercise at HR_H, the $\dot{V}O_2$ started at 88%$\dot{V}O_{2peak}$ and subsequently decreased following reduction of PO to 76%$\dot{V}O_{2peak}$ at T_{lim}. The magnitude of change and relative $\dot{V}O_2$ values for the HR_H trial were similar to those previously reported for running at CHR (91% HR_{peak}) (Bergstrom et al. 2015b) and suggested that the higher end of the vigorous HR range may be required to elicit a $\dot{V}O_2$ responses within a vigorous range and for an appropriate duration (>20min). These $\dot{V}O_2$ responses tracked the decrease in PO that were required to maintain a constant HR for each of the three trials. The composite, for PO collapsed across the HR intensity trials, indicated that the PO decreased relative to the initial value (10% T_{lim}) from 20-100%T_{lim} (Figure 3). A similar pattern was observed for RER and $\dot{V}_E$ during the constant HR trials (Figure 4, 5), which was consistent with the reductions in metabolic demand. These findings were consistent with those of other authors (Boulay et al.1997, Kindermann et al.1979, Mielke et al. 2011, Bergstrom et al. 2015a) who have reported similar change for velocity or PO as well as physiological variables during continuous cycling or running at a constant HR. Thus, the findings of this study supported those of previous studies (Boulay et al. 1997, Kindermann et al. 1979, Mielke et al. 2011, Bergstrom et al. 2015a) and indicated that during running and cycling the $\dot{V}O_2$ responses tracked velocity and PO but were dissociated from HR, which remained constant throughout the trials.

The results of the present study indicated a decrease in metabolic efficiency, reflected by an increase in the oxygen cost ($\dot{V}O_2$) per watt (PO). The decrease in metabolic efficiency was consistent with fatiguing exercise at a constant PO or HR reported (Sawyer et al. 2012, Bergstrom Dissertation. 2014, Bergstrom et al. 2015b, Succi et al. 2023 in press). However, the dissociations between $\dot{V}O_2$ and HR during prolonged cycling at a constant HR differed from the typical responses during constant PO exercise. It has been previously demonstrated that prolonged exercise at a constant PO above the VT leads to an increase in $\dot{V}O_2$ over the course of exercise called the $\dot{V}O_2$ slow component, defined as a progressive increase (>200mL·min^{-1}) in $\dot{V}O_2$ after 3 min of exercise (Whipp et al. 2002, Green. 1997). The $\dot{V}O_2$ slow component has been described to reflect additional contributions of less efficient (higher $\dot{V}O_2$ cost per watt) fast glycolytic (Jones et al. 2011, Succi et al. 2023 in press). However, during exercise anchored to HR, PO is reduced and $\dot{V}O_2$ tracks this response (Succi et al. 2023 in press). Thus, constant HR exercise does not demonstrate a typical $\dot{V}O_2$ slow component response. In this study there was a decrease in metabolic efficiency for the composite across time (10% vs 100%T_{lim}) of the constant HR trials (table 14) that was consistent with the decreases in metabolic efficiency previously reported for constant HR exercise (Bergstrom et al. 2015b). These findings suggested that a $\dot{V}O_2$ slow component, as it is traditionally defined, does not exist for constant HR exercise. Although the typical pattern of a $\dot{V}O_2$ slow component was not demonstrated for constant HR exercise, the decreases in metabolic efficiency are consistent with the phenomenon underlying the $\dot{V}O_2$ slow component. These findings suggested that unique modeling of fatigue during constant HR exercise should be considered.

Continuous exercise at a constant PO above the VT is also associated with a cardiovascular drift, which is defined by a gradual increase in HR after ~10 min of moderate to heavy intensity exercise (Coyle et al. 2001). The cardiovascular drift has been shown to be closely linked to decreases in blood volume from dehydration during sustained exercise and subsequently results in a decrease in stroke volume (SV) (Coyle et al. 2001). Thus, HR must increase to maintain cardiac output (HR x SV). The $\dot{V}O_2$ slow component is linked to the cardiovascular drift as cardiac output must increase to meet the increases in $\dot{V}O_2$ demonstrated during constant PO exercise. However, exercise anchored to HR prevents the appearance of a cardiovascular drift as it is traditionally defined. Because cardiac output changes to meet the metabolic ($\dot{V}O_2$) demand of the exercise (Wasserman et al. 2005), the decreases in PO and $\dot{V}O_2$ over time during the constant HR trials in this study indicated there was a reduction in SV and cardiac output. However, unlike constant PO exercise, the reduction in SV was not related to increases in HR because HR remained constant throughout all of the trials. These findings suggested that additional considerations for modeling cardiovascular efficiency are necessary for constant HR exercise.

In the current study, there were dissociations between RPE and HR that reflected significant increases in RPE from 30% to 100% of T_{lim} for each the constant HR trials. The only parameter that tracked the increases in RPE was RR, which increased relative to the initial value at 70% of T_{lim}. The patterns of responses observed for RR and RPE (Figures 2,6) were consistent with those of previous authors (Bergstrom et al. 2015a, Succi et al. 2023 in press). The RPE and RR responses of the present study, may be best explained by the exercise pressor reflex model which suggests that feedback from small type III and IV afferents, associated with mechano- and metaboreceptors, from the working thigh, leg, and/or respiratory muscles contribute to the respiratory, cardiovascular, and perceptual responses during cycling exercise (Amann et al. 2010, Kaufmann & Hayes. 2002). Therefore, the increase in RPE may be attributed to an increase in the RR and feedback from mechanical and metabo-sensitive group III/IV afferent neurons. It is also possible that, despite dissociations in the patterns of responses for RPE compared to $\dot{V}O_2$ and RER, the reductions in metabolic efficiency provided afferent feedback from the working muscles that contributed to increases in the perceived exertion. In addition to afferent feedback from the working respiratory and skeletal muscles, changes in core temperature have been shown to influence RPE (Coyle et al. 2001). Previous work (Saltin et al. 1968) has demonstrated increases in core temperature of 0.93, 0.69 and 0.61°C in various, temperature-controlled environments of 30, 20, and 10°C, respectively, after only 10 min of exercise. Increased core temperature has been linked to greater perceived exertions (Pandolf et al. 1972). In this study, exercise was sustained on average ~27 to 53 min for all the HR trials. Thus, it is likely that during this duration of exercise there were increases in core temperature that may have also influenced the perception of effort (Coyle et al. 2001).

5.5 Time in the intensity domain

In the present study, the metabolic ($\dot{V}O_2$) demand of the HR trials was also characterized by the time spent within the exercise intensity domains. The moderate intensity domain is defined as work rate that can be performed below the VT (or lactate threshold) and, at a constant PO the $\dot{V}O_2$ will increase initially and reach a steady state within in about 3 min of the task. The heavy intensity domain is defined as the lowest work rate at which blood lactate increases above resting levels and the highest work rate at which blood lactate concentration reaches a steady state level. In this study, the heavy domain was defined as the time spent between the VT and RCP. The severe intensity domain exercise is defined as the point where $\dot{V}O_2$ and blood lactate cannot be stabilized, but rather rise until $\dot{V}O_2$ reaches $\dot{V}O_{2peak}$ (Gaesser & Poole. 1996). This point was estimated to be PO above the RCP in this study. The metabolic demands of an exercise task are unique depending on the intensity domain. For example, exercise in the heavy and severe domains place increasing demands on the buffering capacity for metabolic byproducts, but exercise within the moderate domain does not (Gaesser & Poole. 1996). In addition, the sustainability of an exercise bout is dependent on intensity relative to these domains, whereby exercise in the heavy domain can generally be sustained for at least 30 min, but exercise in the severe domain is typically not sustainable for more than 15 to 20 min (Gaesser & Poole. 1996, Poole et al.1988). Therefore, to better understand the relative metabolic demands of constant HR exercise at the HR_L, HR_M, and HR_H, the time spent in each intensity domain was calculated as the sum of the time that PO correspond to severe (>PORCP), heavy (<PORCP,>POVT), and moderate (<POVT) domains and included the time to get to the designated HR.

During the HR_L trial, the average time spent in the severe, heavy, and moderate intensity domains at was 0.00±0.00, 2.33±3.74, and 53.50±15.57 min, respectively. Nine of the 12 participants were able to sustain exercise for 60 min and those participants spent the majority of the trial within the moderate intensity domain (60.33-62.33). The remaining 3 participants who were able to sustain exercise long enough to be termed sustainable (≥20 min) also spent the majority of the time within the moderate intensity domain (18.67-42min). These participants, however, spent more time in the heavy intensity domain (3-10 min) compared to the 9 participants who sustained exercise for 60 min (0.00-2.67 min), before traversing to the moderate intensity domain. Taken together, these results suggested that exercise performed consistently at the HR_L would likely not stimulate improvements in buffering capacities because of the limited time spent in the heavy intensity domain. Therefore, HR_L may be an intensity that is out of the desired range for CE exercise prescription.

During the HR_M trial, the average time spent in the severe, heavy, and moderate intensity domain was 0.17±0.48, 5.67±5.27, and 43.58±23.07 min, respectively. Seven of the 12 participants who were able to sustain exercise for 60 min spent the majority of the trial within the moderate intensity domain (54.00-63.00min). Three of the 12 participants who were able to sustain exercise long enough to be termed sustainable (≥ 20min) also spent the majority of the time within the moderate intensity domain (15.33-32.67 min) with limited time in the heavy or severe domains (< 10min). Two participants who were not able to sustain exercise for at least 20 min spent the majority of time in the heavy domain (12.67-14.33 min), compared to the 10 participants that were able to sustain exercise for ≥20 min (1.00-9.33 min), before traversing to the moderate intensity domain. Thus, on average and for a majority (10 of 12) of participants, the HR_M trial reflected an exercise intensity in the moderate domain. These results suggested that the HR_M may not be an intensity that is high enough to stimulate metabolic adaptations to improve buffering capacities for the majority of participants.

During the HR_H trial, the average time spent in the severe, heavy, and moderate intensity domain was 1.78±1.98, 10.53±12.11, and 17.81±18.40 min, respectively. One of the 12 participants was able to sustain exercise for 60 min and spent majority of the trial within the moderate intensity domain (59.33 min). Seven of the 12 participants were able to sustain exercise long enough to be termed sustainable (≥20 min). However, only 2 of those participants spent at least 20 min within the heavy intensity domain before traversing to the moderate intensity domain, while the other 5 participants spent the majority of the trial in the moderate domain. The participants that spent majority of the time at HR_H within the severe intensity reached exhaustion before the desired minimum of 20 min of exercise. Specifically, the 4 participants who were not able to be sustained exercise for at least 20 min spent more time in the severe intensity domain (2.67-6.33min) before traversing to the heavy intensity domain compared to the participants that were able to sustain exercise for ≥ 20min (1.00-2.67 min). These results suggested that the HR_H may be an intensity that is high enough to stimulate adaptation for a small percentage of individuals because on a participant-by-participant basis 2 of the 12 participants spent ≥ 20 min within the heavy intensity domain before traversing to the moderate intensity domain. Therefore, HR_H may be an intensity exercise that is sustainable (≥ 20min) for some, but not the majority of, individuals and at an intensity appropriate to stimulate improvements in metabolic byproduct buffering capacities.

Previous work (Beaver et al. 1986, Francis et al. 2010) has demonstrated that exercise performed in the severe and heavy intensity domains requires anaerobic energy production to supplement the aerobic pathways, which results in the generation of metabolic byproducts (Jones et al. 2008), ultimately resulting in fatigue. Across all three intensities there were decreases in $\dot{V}O_2$ and PO throughout the HR_L, HR_M, and HR_H trials. The results of this study demonstrated individual differences in the sustainability of exercise during the trials at HR_L, HR_M, and HR_H that were based on the amount of time spent within the severe intensity domain and also around the transition phase between heavy and severe intensity domains. Therefore, on a participant-by-participant basis, the participants that spent prolonged time within the heavy or severe domain were unable to recover or use stored energy sources at a rate leading to fatigue, and the participants that were able to traverse to moderate intensity domain were able to sustain exercise for ≥ 20 min.

5.6 Summary

The results of the present study provide unique information regarding exercise anchored at a constant HR within the ACSM recommended range for vigorous intensity (77-95%HR_{peak}). Our findings showed that at HR_L was sustainable for ≥ 20 min for all of the participants, while 83% of the participants sustained exercise for ≥ 20 min at HR_M, and 67% of the participants were able to sustain exercise for ≥ 20 min at HR_H. However, at HR_L none of the participants were within the recommended range for $\dot{V}O_2$ (64-90% $\dot{V}O_{2peak}$). At HR_M, 5 of the 12 participants were able to sustain exercise for more than 20 min within the recommended range, and at HR_H ~58% (7 of 12 participants) were able to sustain exercise for at least 20 min within the recommended range. During the exercise at HR_L, HR_M, HR_H, the PO was reduced to maintain the selected HR and the $\dot{V}O_2$ responses tracked the changes in PO. The $\dot{V}_E$ and RER followed a similar pattern for each trial. The decreases in PO observed during the trials allowed the participants to traverse the intensity domains rapidly to minimize the amount of time spent within the severe intensity domain. These results suggested that the participants that spent more time within the heavy and severe intensity domains required anaerobic energy reconstitution, which ultimately may have resulted in fatigue (Jones et al. 2008, Succi et al 2023 in press) and task failure before 20 min.

There were increases in the perception of efforts during all of the HR trials ($p < 0.001$). The RR and the RPE followed a similar pattern, and those results were similar to those found in constant work rate exercise within the heavy and severe intensity domain (Amann et al. 2010, Succi et al. 2023 in press). These results suggested that the perception of effort but not $\dot{V}O_2$ or HR, can be used to identify fatigue during continuous exercise at HR_L, HR_M, and HR_H. The decrease in $\dot{V}O_2$ throughout the HR trials suggested that RPE and fatigue were not primarily related to O_2 availability but was more closely linked to RR. These may have been influenced by group III/IV afferent feedback from the respiratory muscles. It is also possible that RPE was driven by increases in core temperature that have been demonstrated for prolonged exercise however, we did not measure core temperature (Coyle et al. 2001).Collectively, the current findings indicated HR_L reflected an intensity that was too low to meet the current exercise prescription guidelines for most individuals, while the HR_M may be an intensity that is high enough to meet the minimum range of the guidelines, on average, but was not sufficient to elicit the desired metabolic responses for the majority of the individuals. The HR_H may be an intensity high enough to elicit the desired metabolic responses, but only 58% of the participants were able to maintain the trial at the recommended metabolic rate for $\geq$ 20 min. Therefore, the results of this study indicated that exercise held constant at a percent of HR_{peak} cannot consistently be used to prescribe a desired metabolic stimulus.

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Walmart Pharmacy| Pharmacy Technician	**2018- 2022**

Awards and Honors

Department of Kinesiology and Health Promotion Student Research Award	**Spring 2023**
John Edwin Partington & Gwendolyn Gray Partington Scholarship	**2022-2023**
Dean's List, University of Kentucky	**Fall 2019**
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Research

Manuscripts (In preparation)

Kwak, M., Succi, P.J., Benitez, B., **Gustave, D.,** and Bergstrom, H.C. Examination of intra- and inter-rater reliability of the ventilatory threshold and respiratory compensation point. To be submitted to: *Journal of Strength and Conditioning Research.*

Abstracts

Kwak, M., Succi, P.J., Benitez, B., **Gustave, D.,** and Bergstrom, H.C. Examination of intra- and inter-rater reliability of the ventilatory threshold and respiratory compensation point. (July 2022).

D.Gustave, P.J. Succi, B. Benitez, M. Kwak, J.L. Clasey, K.R Lanphere, H.C. Bergstrom. A preliminary analysis of responses to exercise anchored to vigorous intensity heart rates. (February 2023).

D.Gustave, P.J. Succi, B. Benitez, M. Kwak, J.L. Clasey, K.R Lanphere, H.C. Bergstrom. Responses to exercise anchored to vigorous intensity heart rates. (To be Presented at the American College of Sport Medicine National, May 2023).

D.Gustave, P.J. Succi, B. Benitez, M. Kwak, J.L. Clasey, K.R Lanphere, H.C. Bergstrom. Responses to cardiorespiratory endurance exercise anchored to a vigorous heart rate. (Submitted for presentation at the National Strength in Conditioning Association, July 2023)

P.J. Succi, B. Benitez, M. Kwak, T.A. Butterfield, H.J. Pfeifer, **D. Gustave**, H.C. Bergstrom. Performance fatigability, muscle excitation, and neuromuscular efficiency after cycling anchored to vigorous ratings of perceived exertion. (Submitted for presentation at the National Strength in Conditioning Association, July 2023)

B. Benitez, P.J. Succi, M. Kwak, **D. Gustave**, H.C. Bergstrom. Sex-Specific Differences in Fatigability During Bilateral Vs Unilateral Maximal Isometric Exercise to Task Failure. (Submitted for presentation at the National Strength in Conditioning Association, July 2023)