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**DETERMINATION OF CRITICAL REST INTERVAL FROM REPEATED
SPRINT ABILITY TESTING**

by
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B.S. Rutgers University, 2009

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Sport and Exercise Science
in the College of Education and Human Performance
at the University of Central Florida
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ABSTRACT

The critical power (CP) concept has been used to determine the appropriate rest interval during intermittent exercise through the investigation of critical rest interval (CRI). Repeated sprint ability (RSA) testing has been developed to define the athlete's ability to recover and maintain maximal effort during successive bouts. The CP model has been used to understand the physiological responses involved with intermittent exercise delineating between severe and heavy exercise intensity domains. The primary purpose of this study was to determine the CRI from the work-time relationship given by RSA testing using varying work to rest ratios. The secondary purpose was to determine the validity of CRI by evaluation of physiological responses above and below estimated rest interval values during intermittent cycling.

Twelve recreationally trained males (mean \pm SD; age 24.1 ± 3.6 yr; height 175.8 ± 7.0 cm; weight 77.6 ± 12.8 kg; $\dot{V}O_{2\text{peak}}$ 43.3 ± 5.6 ml/kg/min; Body Fat (%) 24.5 ± 4.4) were recruited for this study. Participants performed a graded exercise test to determine $\dot{V}O_{2\text{peak}}$ and peak heart rate. Eight participants completed the same three RSA protocols with 6s maximal sprints and varying rest intervals (12-24s) on a cycle ergometer. Intermittent critical power (ICP) was calculated through the linear total work (TW) and time-to-exhaustion (TTE) relationship, whereas CRI was estimated using the average work per sprint and ICP. Seven subjects completed trials above and below estimated CRI to evaluate the validity of this estimate through the examination of the physiological responses. Breath-by-breath oxygen consumption ($\dot{V}O_2$) and heart rate (HR) values were recorded during the validation trials. One-way repeated measures analysis of variance (ANOVA) was used to analyze the variables from the RSA trials. Paired samples t-tests were performed to compare performance and physiological variables above or below CRI during the validation trials. Two-way repeated measures ANOVA was used

to examined the changes in oxygen consumption ($\dot{V}O_2$), HR, mean power (MP), and TW throughout the validation trials.

Significant differences ($p < 0.1$) were found for the number of intervals completed, TTE, average work per sprint, peak and mean $\dot{V}O_2$ between RSA protocols. Linearity between TW and TTE was $r^2 = 0.952 \pm 0.081$. During the validation trials, TTE was significantly greater in the above versus the below CRI trial ($2270.43 \pm 941.15s$ vs. $1511.00 \pm 811.0s$). Furthermore, blood lactate concentration ($8.94 \pm 4.89\text{mmol/L}$ vs. $6.56 \pm 3.45\text{mmol/L}$), Ave $\dot{V}O_2$ ($2.05 \pm 0.36\text{L/min}$ vs. $1.78 \pm 0.26\text{L/min}$), $\dot{V}O_{2\text{peak}}$ ($2.84 \pm 0.48\text{L/min}$ vs. $2.61 \pm 0.43\text{L/min}$), and AveHR ($151.14 \pm 18.46\text{bpm}$ vs. $138.14 \pm 17.51\text{L/min}$) were significantly greater in the below CRI trial when compared to the above CRI trial. Significant interactions were found between above and below trials within minimal $\dot{V}O_2$ response ($F = 6.886$, $p = 0.024$, $\eta^2 = 0.534$) to the recovery intervals and maximal HR ($F = 4.51$, $p = 0.016$, $\eta^2 = 0.429$) response to the work intervals. During the above CRI trial, minimal $\dot{V}O_2$ response decreased over time (51-43% $\dot{V}O_2$ peak) while maximal HR response achieved a steady state level (81-84%HRpeak). Conversely, minimal $\dot{V}O_2$ response during the below CRI trial achieved a steady state level (54-58% $\dot{V}O_2$ peak), whereas maximal HR response increased over time (84-90%HRpeak).

The relationship between TW and TTE is appropriate for use with RSA testing with varying rest intervals. The differing physiological response during the validation trials may reflect changes in energy system contribution. In conclusion, CRI distinguished between physiological responses related to exercise intensity domains in a manner similar to CP estimates determined from other testing and exercise modalities.

TABLE OF CONTENTS

LIST OF FIGURES	vi
LIST OF TABLES	vii
CHAPTER I: INTRODUCTION.....	1
Purpose	7
Research Questions	8
Hypotheses	8
Operational Definitions	9
Abbreviations	9
Delimitations	10
Assumptions	10
Limitations	11
CHAPTER II: REVIEW OF LITERATURE	12
Critical Power and Velocity	12
Metabolic requirements/Energy systems	21
Mathematical Modeling	30
Repeated Sprint Ability	38
Intermittent Critical Power and Velocity	47
CHAPTER III: DESIGN AND METHODOLOGY	58
Participants	58
Research Design	58
Variables.....	59
Instrumentation.....	59
Initial Screening and Testing Methods	60
Data Analysis	65
CHAPTER IV: RESULTS.....	68
Repeated Sprint Ability Testing.....	68
Critical Rest Interval Estimation.....	69
Validation Trials.....	69
CHAPTER V: DISCUSSION.....	74

Repeated Sprint Ability Testing	74
Critical Rest Interval Estimation	75
Validation Trials.....	78
Conclusions	88
APPENDIX A: LIST OF TABLES	89
APPENDIX B: LIST OF FIGURES.....	95
APPENDIX C: IRB APPROVAL	100
APPENDEX D: INFORMED CONSENT	103
REFERENCES	112

LIST OF FIGURES

Figure 1: Maximal $\dot{V}O_2$ response during the validation trials above and below critical rest interval (CRI) relative to maximal oxygen consumption ($\dot{V}O_{2peak}$) from the graded exercise test	96
Figure 2: Minimal $\dot{V}O_2$ response during the validation trials above and below critical rest interval (CRI) relative to maximal oxygen consumption ($\dot{V}O_{2peak}$) from the graded exercise test	96
Figure 3: Maximal heart rate response during the validation trials above and below critical rest interval (CRI) relative to maximal heart rate (HR _{peak}) from the graded exercise test	97
Figure 4: Minimal heart rate response during the validation trials above and below critical rest interval (CRI) relative to maximal heart rate (HR _{peak}) from the graded exercise test	98
Figure 5: Peak power relative to initial maximal power (P _{max}) values during the validation trials above and below critical rest interval (CRI)	98
Figure 6: Mean power (MP) during the validation trials	99
Figure 7: Average total work (TW) during the validation trials	99

LIST OF TABLES

Table 1: Descriptive data for participants	90
Table 2: Comparison of each repeated sprint ability (RSA) protocol	91
Table 3: Comparison of participants who performed the same repeated sprint ability (RSA) protocols.....	92
Table 4: Estimated values for critical rest interval (CRI) and anaerobic working capacity (W')	93
Table 5: Comparison of validation trials above and below critical rest interval (CRI)	94

CHAPTER I: INTRODUCTION

The Critical Power (CP) concept allows us to more fully understand the framework of fatigue and exercise intolerance. CP is a function of both the aerobic and anaerobic energy systems differentiating between heavy and severe intensity exercise (Jones et al., 2010, Soares-Caldeira et al., 2012, Morton 2006). CP assumes that the aerobic energy supply features an unlimited capacity, the anaerobic energy supply features a limited capacity, and that exhaustion occurs when all of the anaerobic working capacity (W') is depleted (Morton 2006). W' is associated with anaerobic working stores such as phosphocreatine (PCr) and glycogen (Jones et al., 2010, Miura et al., 2002). In turn, the buffering process, rate-limiting mechanisms, and the enzymes involved in glycolysis may also determine W' (Green et al., 1994). Additionally, W' has been shown to be positively correlated with active muscle volume, muscle cross sectional area (CSA), and peak O_2 consumption during exercise (Miura et al., 2002). Thus, exercising at intensities above CP will deplete finite fuel storage and eventually lead to maximal aerobic capacity ($\dot{V}O_{2max}$) (Jones et al., 2010, Miura et al., 2002). This can be represented by the hyperbolic power-time relationship (Jones et al., 2010). With this graphical representation, the CP is calculated via a drawn asymptote parallel to the power-axis. This value is defined as CP which is the highest sustainable intensity that can theoretically be maintained for an extended period of time without eliciting $\dot{V}O_{2max}$ (De Lucus et al., 2013). Further, the amount of work that can be done above CP, or anaerobic working capacity (W'), can be calculated as the curvature constant of the power-time relationship.

A number of linear and nonlinear models have been used to analyze the power-time relationship (Housh et al., 2001). Of these models, there are inherent differences in CP estimates. The nonlinear-2 hyperbolic model is depicted as $t = W' / (P - CP)$, where t = time to

exhaustion and P = power output. The inconsistency may lie within the analysis of nonlinear data converted into linear form (Bull et al., 2000, Housh et al., 2001). The linear power model (L-P) is expressed using two equations $TW = P \times t$ and $TW = W' + CP \times t$, where TW = total work, P = power, and t = time to exhaustion. Setting the two equations equal to each other ($P \times t = W' + CP \times t$) and dividing by P allows for a power versus inverse of time comparison (Bull et al., 2000). Alternatively, the linear total work model (L-TW) model is based on the regression of total work versus time, with the slope of this linear regression line estimating CP and the y-intercept estimating W' (Fukuda et al., 2011, Bull et al., 2000). The linear total work model (L-TW) has demonstrated highly linear relationships between total work and time to exhaustion for cycle ergometer work bouts (Monod & Scherrer, 1965, Moritani et al., 1981, Bull et al., 2000). The L-TW and the hyperbolic model have demonstrated close mathematical relationships with power and time; Bull et al. (2000) reported $r^2 = .997-1.000$ and $.894-1.000$ for each model respectively and Moritani et al. (1981) reported $r^2 = .982-.998$ for the L-TW model. In fact, Jenkins & Quigley (1991) found a strong correlation between TW and the y-intercept (W'). The L-TW and nonlinear-2 models have shown to provide similar estimates of CP and critical velocity, the running analog to CP , compared with all other mathematical models (Bull et al., 2000, Housh et al., 2001).

The CP model has recently been used to understand the physiological responses involved with intermittent exercise. Chidnok et al. (2012) distinguished physiological responses above and below CP showing that when constant work rate above CP was performed it elicited an increase in inorganic phosphate (P_i), while at the same time a decrease in intramuscular PCr and pH levels until volitional fatigue was attained. On the other hand, when constant work rates below CP were performed observable levels of P_i , PCr , and pH were steady. Intermittent

exercise allows for clearance of some of these fatigue-related metabolites and PCr to be resynthesized which postpones exhaustion and reduces the accumulation of fatigue-related by-products to a certain extent before volitional fatigue (Chidnok et al., 2012). In other words, intermittent exercise depletes anaerobic stores and progressively accumulates metabolic waste (Chidnok et al., 2012). Anaerobic working capacity is rate limited and may be modelled as the energy immediately available for short bursts of sprints until these reserves are exhausted (Morton 2006, Fukuda et al., 2011). During intermittent exercise, the aerobic system attempts to replenish those reserves, to a certain extent, during the rest interval (Morton 2006, Fukuda et al., 2011). From a theoretical standpoint, CP is the rate of energy reconstitution dictated by the available W' and the need for energy replenishment because it acts as the link between the aerobic and anaerobic energy supplies (Morton 2006, Housh et al., 2001). Therefore, CP acts as the rate limiting factor during high intensity exercise (Morton 2006). Moreover, when the power required during exercise is greater than CP, the anaerobic system must utilize energy stores via depletion of W' (Morton 2006). Alternatively, when the power required is less than or equal to CP, the anaerobic system is not fully taxed and W' will not become depleted (Morton 2006). Individuals with a high anaerobic working capacity may not require a fast rate of PCr replenishment during the initial bouts of exercise, but performance may be adversely impacted during successive bouts when replenishment is provided aerobically (Fukuda et al., 2011, Pereira et al., 2009). Subsequently, anaerobically trained individuals would need more time to recover than aerobically trained individuals during intermittent exercise (Morton 2006, Fukuda et al., 2011). Therefore, recovery intervals allow for restoration of W' with the magnitude of this repletion related to the duration and intensity of the recovery interval. In turn, this can forecast exercise tolerance and help prescribe effective work-to-rest ratios during interval training

(Chidnok et al., 2012, Pettitt et al., 2013). However, inconsistencies lie between critical power in continuous and intermittent exercise and the validity of intermittent critical power exercise has yet to be fully explored (Soares-Caldeira et al., 2011). Morton & Billat (2004) successfully adapted the CP model for intermittent exercise as long as the power output during the work and rest intervals are greater than CP, which ensures partial refilling of anaerobic capacity during each rest interval (Morton & Billat, 2004).

Intermittent protocols have been conducted to illustrate the different physiological responses ($\dot{V}O_2$, HR, lactate, and RPE) compared to continuous protocols (Okuno et al., 2011, Soares-Caldeira et al., 2011). Intermittent critical power (ICP) can be defined as the highest theoretical intensity that can be maintained during repeated intervals for a prolonged period of time without eliciting $\dot{V}O_{2max}$ (Fukuda et al., 2011). ICP has been correlated with maximal aerobic power (MAP) and $\dot{V}O_{2max}$ suggesting that estimates may be used as an aerobic fitness index (Okuno et al., 2011). However, the relationship between W' determined during continuous and intermittent exercise is less clear. For example, Soares-Caldeira et al. (2011) showed no correlation between continuous and intermittent W' , while the opposite was observed by Okuno et al. (2011). Okuno et al. (2011) showed no difference between intermittent maximal lactate steady state and exercise at ICP. Furthermore, Soares-Caldeira et al. (2011) did not reveal statistically different lactate concentrations during or following intermittent and continuous CP protocols. Since the basis for CP is the highest intensity the muscles can sustain for a prolonged period of time, physiological responses should experience steady state at ICP (Okuno et al., 2011). Supporting this notion, Okuno et al. (2011) reported similar power outputs, HR, $\dot{V}O_2$, and lactate between ICP and intermittent maximal lactate steady state.

The CP concept has also been used to determine the appropriate rest interval during intermittent exercise through the investigation of critical rest interval (CRI). CRI is the theoretical amount of rest needed to complete successive bouts of exercise and, therefore, estimates the amount of rest needed before utilizing anaerobic working capacity (Pereira et al., 2009, Fukuda et al., 2011). With a rest period too short, rapid utilization of PCr and glucose will deplete W' more rapidly than the aerobic system can replenish W' . On the other hand, a longer rest period gives the aerobic system ample time to replenish PCr stores, clear out fatigue related by-products, and restore the anaerobic energy supply. Pereira et al. (2009) was the first study to manipulate work to rest ratios to determine critical rest interval (CRI). These researchers determined CRI between successive vertical jumps utilizing the CP model (Pereira et al., 2009). Different rest periods were used in order to elicit fatigue in 1 to 10 min and produce a different number of vertical jumps, total external work, and time to exhaustion. Estimated CRI was predicted and tested for validity given their performance in prior sessions (Pereira et al., 2009). Recently, Fukuda et al. (2011) applied the CRI calculation to examine suitable rest periods during interval running. The researchers estimated CRI through the analysis of the total distance ran and the number of intervals completed via ICP testing, thus supporting that appropriate rest periods can be estimated through the use of variables from intermittent critical velocity (ICV) testing (Fukuda et al., 2011). However, neither study examined the O_2 consumption during validation trials above and below the estimated CRI values.

Interval training has become a popular method incorporated into conditioning programs since most team sports consist of repeated sprints with variable rest periods (Morton & Billat 2004, Fitzsimons et al., 1993). Interval training challenges the mechanisms of each energy system and individuals who can maintain near maximal sprints the longest have a greater

resistance to fatigue, allowing them to perform at higher levels further into a match (Fitzsimons et al., 1993, Morton, 2006, Glaister et al., 2005). In an effort to quantify potential performance as well as training response, exercise scientists have developed protocols to measure repeated sprint ability (RSA) defined as the athlete's ability to recover and maintain maximal effort during successive sprints (Turner and Stewart, 2013). The appropriate RSA protocol should resemble a work to rest ratio similar to that required in the competition environment (Turner and Stewart, 2013). Power is the byproduct of the intensity of muscle contraction and the rate at which adenosine tri-phosphate (ATP) is being consumed (Turner and Stewart, 2013). However, various energy systems contribute to the rate of ATP regeneration which is dependent upon the exercise intensity and the duration of the rest period (Turner and Stewart, 2013). Anaerobic glycolysis replenishes ATP during short sprints, but the oxidative system supplies ATP for PCr resynthesis over successive recovery intervals (Dupont et al., 2002, McMahon & Jenkins, 2002, Dupont et al., 2010). Hence, PCr resynthesis is limited by the length of the rest period and is dependent upon the oxygen availability (Glaister et al., 2005, Dupont et al., 2010, Turner and Stewart, 2013). During recovery, $\dot{V}O_2$ will remain elevated above baseline and the key role of the aerobic system will be to return the body to homeostasis. A faster O_2 uptake relates to quicker recovery, reduced fatigue, and reduced performance decrements (Glaister et al., 2005, Dupont et al., 2010). Depending on the number of sprints needed, the rest period will need to be sufficient enough to resynthesize PCr, remove metabolic waste, and oxidize lactate (Glaister et al., 2005, Billaut & Basset, 2007, Turner and Stewart, 2013).

The most common protocol emerging out of the literature is 6s of maximal sprints with 24s active, passive, or static rest (Morin et al., 2011). Likewise, Fitzimmons et al. (1993) examined the degree of fatigue on a cycle ergometer from each sprint starting from the first.

Subjects performed six 6s sprints at or above 95% of maximum work with 24s rest and showed consistent and significant decrements in performance in each sprint (Fitzimmons et al., 1993). Due to the contribution of other metabolic pathways, a single maximal sprint of 6s will deplete PCr stores 30-55% (Turner & Stewart, 2013, Glaister, 2005). The extent to which PCr contributes to repeated sprints depends on the PCr replenishment during the rest interval (Glaister 2005). Glaister et al. (2005) determined that a longer rest interval (30s), during repeated sprints, had significant effects on peak and mean power output. Conversely, a 10s rest recovery increased hydrogen ion concentration and may interfere with various enzymatic activities that lead to ATP production (Glaister et al., 2005). The longer rest period most likely allowed PCr to contribute to power over the course of each sprint best explaining the difference between rest periods (Glaister et al., 2005). Likewise, intracellular Pi is known to result in fatigue during high intensity exercise because it inhibits calcium release in the sarcoplasm reticulum and the removal of Pi and PCr resynthesis is oxygen dependent (Glaister et al., 2005).

In an effort to better understand the prescription of interval training and the quantification of CRI, this study examined the CP concept utilizing different work-to-rest ratios during RSA testing on a cycle ergometer. Furthermore, this study examined the rate of oxygen consumption during work and rest intervals within the various testing sessions. Because previous studies have not employed the use of RSA testing in order to calculate CRI, the aim of this investigation was to determine and validate CRI by evaluating oxygen consumption above and below estimated rest interval values.

Purpose

1. To examine the work-time relationship during repeated sprint ability testing.

2. To determine the critical rest interval from the results of repeated sprint ability testing using varying work to rest ratios.
3. To determine the validity of critical rest interval by evaluation of the physiological response above and below estimated rest interval values during intermittent cycling.

Research Questions

1. Will oxygen consumption, total work, and time-to-exhaustion differ between the various RSA protocols?
2. Can the relationship between work to rest ratio and time to exhaustion from RSA on a cycle ergometer be used to estimate CRI?
3. Can CRI calculated from repeated sprint ability testing be validated through the examination of oxygen consumption and blood lactate concentrations?

Hypotheses

1. The TTE and total work will differ between each RSA test session.
2. The mean $\dot{V}O_2$ during each RSA protocol will not differ, however the $\dot{V}O_2$ during shorter rest intervals will remain higher than the longer rest intervals.
3. The peak $\dot{V}O_2$ during each RSA protocol will not differ from the peak $\dot{V}O_2$ from the GXT.
4. Performance below the calculated CRI value will result in attaining maximal aerobic capacity and an exponential rise in blood lactate.
5. Performance above the calculated CRI value will result in steady state aerobic capacity and blood lactate.

Operational Definitions

Critical rest interval (CRI) – The smallest theoretical rest period that allows for the maintenance of 6s cycling sprint intervals for a prolonged period of time without inducing fatigue. This will be determined by examining the linear relationship between total work done and time-to-exhaustion.

Anaerobic working capacity (W') – The amount of work that can be done above critical power during the use of limited storage capacity and the accumulation of fatiguing by-products. This will be calculated as the y-intercept of the regression line determined by the relationship between total work done and time-to-exhaustion.

Repeated sprint ability (RSA) – The ability to complete work bouts of 6s maximal sprints interspersed with varying rest periods

Abbreviations

$\dot{V}O_2$ peak – Maximal Oxygen Consumption

RSA – Repeated Sprint Ability

W' – Anaerobic Working Capacity

TW – Total Work

TD – Total Distance

PPO – Peak Power Output

TTE – Total Time to Exhaustion

VT – Ventilatory Threshold

ICP – Intermittent Critical Power

CRI – Critical Rest Interval

GXT – Graded Exercise Test

RSA – Repeated Sprint Ability

Pmax – Initial Peak Power Output

RPR – Rate of Perceived Readiness

Delimitations

Twenty men between the age of 18 and 35 were recruited for this study. All participants completed a Confidential Medical and Activity Questionnaire, Physical Activity Readiness Questionnaire and a written informed consent prior to testing. To be included in this study, participants were healthy and free of disease or injury. Also, participants enrolled in this study were recreationally trained with a minimum of two days per week and a minimum aerobic capacity of 35ml/kg/min. Participants maintained their normal dietary and nutritional supplementation while enrolled in the study.

Assumptions

Theoretical Assumptions

1. Participants answered the Confidential Medical and Activity Questionnaire and Physical Activity Readiness Questionnaire accurately and truthfully.
2. Participants did not engage in stressful exercise 2-3 days prior to testing.

3. Participants gave maximal effort on the all testing measures.
4. Participants maintained and did not significantly alter their diet throughout the duration of the study.
5. Participants completed all RSA and validation sessions.
6. Participants maintained a relatively standard sleep cycle.

Statistical Assumptions

1. The sample was randomly selected from the population.
2. Dependent variables were normal distributed.
3. Variability of the dependent variables were homogenous across testing sessions.
4. Observations were independent of one another.

Limitations

1. Participants were recruited primarily from the University of Central Florida; therefore the process of participant selection may not have been truly random.
2. Participants were only be those who volunteer for the study, which may have limited a truly random selection.
3. Due to the amount of time required during the 5 week testing period, participant withdrawal from the study was a concern.
4. Actual dietary consumption was not be measured and daily dietary fluctuations and nutritional supplements may have occurred throughout the study which may impacted the results of the study.

CHAPTER II: REVIEW OF LITERATURE

Critical Power and Velocity

Monod, Scherrer, 1965

The work capacity of a synergistic muscle group

The focus of this study was to better understand the conditions of local muscular fatigue. The authors defined the relationship between the amount of work done before muscular fatigue and the conditions of a non-fatiguing task. A muscle's CP is determined by measuring its work capacity by doing a series of muscular work tests at various power levels. Dynamic work by a muscle is equal to the load (in kg) multiplied by the displacement of the muscle (in m). Therefore when positive work is done, the load is lifted. During a dynamic task, muscle performs a certain amount of work (W_{lim}) within a specific amount of time (t_{lim}) before fatigue. In order to assess this, three muscular work tests are considered. They are performed at three different intensities (power) resulting in three different times to exhaustion and total work done. A linear relationship is formed between time and work producing the equation, $W = a + b(t)$, where W is the total amount of work done, a is the muscle's energy reserve, b is the CP of dynamic work, and t is the TTE. When considering dynamic work, multiple tests have to be completed to exhaustion since CP is not directly measurable. Power is analogous to work only with dynamic work while the critical rate of static work has a dimension of force. In terms of intermittent static work, this level of force depends on the proportion between the duration of contraction phases and t_{lim} . Therefore, work is dependent on the local muscular energy reserve and the reconstitution rate connected to blood flow. Thereby, prolonged activity can occur when

power does not exceed CP and one can state the maximal amount of static or dynamic work a muscle can perform in a given time.

Miura, Endo, Sato, Sato, Barstow, Fukuba, 2002

Relationship between the curvature constant parameter of the power-duration curve and muscle cross-sectional area of the thigh for cycle ergometry in humans

The aim of this study was to determine the relationship between W' , peak accumulated O_2 deficit, and muscle CSA of the thigh during high intensity exercise on a cycle ergometer. Seventeen healthy males between the ages of 21 and 41 participated in this study. Each participant performed four high intensity constant workloads between 90-135% $\dot{V}O_{2peak}$ while the power-time relationship was analyzed. The W' derived from the hyperbolic power-time relationship may reflect the mechanical output of contracting muscles and the peak O_2 deficit may be an estimate of anaerobic chemical energy input. Therefore, W' can reflect a muscle's limited energy storage of PCr, glycogen, and ATP concentrations. The muscle's fat free volume showed a positive correlation with W' ($r = 0.59, P < 0.01$). Similarly, peak O_2 deficit was reported to have a strong correlation with CSA of the thigh ($r = 0.54, P < 0.05$). Furthermore, W' and peak O_2 deficit showed a positive correlation ($r = 0.63, P < 0.005$). The capacity of muscle to provide anaerobic ATP production during high intensity exercise should depend on the energy stores within the muscle and PCr, glycogen, ATP are significant determinants of W' . However, these energy stores differ among fiber types, but despite the difference in fiber types, the size of the muscle is a significant predictor of W' and accumulated peak O_2 deficit.

Morton, 2006

The critical power and related whole-body bioenergetic models

The purpose of this review was to define CP and to explain the evolutionary process of its expansion. Since CP is a function of both aerobic and anaerobic, it can be considered as two energy supplying vessels that are connected by a fixed diameter (CP). The anaerobic vessel is regarded as limited energy storage since most of its energy is derived from phosphates and glycolysis leading to lactate accumulation. On the other hand, the aerobic vessel contains an unlimited amount of fuel as it derives its energy from oxidative phosphorylation and primarily lipids. Power can no longer be maintained when the anaerobic vessel is depleted (W'), but the rate at which it can be depleted is unlimited as long as power output is greater than CP. However, when power is less than or equal to CP, energy from the anaerobic vessel is not required and will not be emptied.

Interval training can be an effective training strategy and has been shown to increase W' and CP since it taxes all energy supply mechanisms. Additionally, hypoxic conditions would reduce the aerobic vessel depth rather than constrict the flow of CP, but hyperoxia would have the opposite effect. During intermittent exercise, intense work periods drain the anaerobic vessel; however the vessel becomes replenished by the aerobic vessel during subsequent rest periods. However, this process does not imply limitless work as the anaerobic vessel depletes at a much quicker rate than the aerobic vessel can replenish. Therefore, exercise will cease once the entire anaerobic vessel is depleted.

The CP model was first expressed as a hyperbolic relationship between work and time. A linear version of this relationship revealed $W = W' + CPt$, where W is total work, and t is time

to exhaustion. Thus, CP is considered the slope and W' is considered the y-intercept. In order to estimate these parameters, individuals need to complete at least two separate exhaustive trials with different, but constant power outputs. The mathematical equations based on mechanical power and derived from total work and endurance time may predict human performance.

Jones, Vanhatalo, Burnley, Morton, Poole, 2010

Critical Power: Implications for Determination of $\dot{V}O_2\text{max}$ and Exercise Tolerance

This review covers the historical basis, the application of CP, mathematical modeling, and the practical applications of CP. Historically, the power-time relationship is founded on the coordinated function and distinction between the aerobic and anaerobic systems. CP represents the border between heavy and severe exercise intensity where power output leads to $\dot{V}O_2\text{max}$. In trained individuals, lactate threshold (L_T) and CP lie close to one another, but CP is always at the higher $\dot{V}O_2$. In fact, CP may be the point at which $\dot{V}O_2$ and blood lactate stabilizes which lies halfway between $\dot{V}O_2\text{max}$ and L_T (80% $\dot{V}O_2\text{max}$) in physically active, but not highly trained males. Mechanically, CP may increase after short-term continuous endurance training and after high intensity interval training, but it may decrease with exercise in hypoxic conditions. Likewise, W' can be increased by short-term sprint interval training, after training interventions designed to increase CP, and possibly by creatine loading. W' is related to fatigue-related metabolites such as, H^+ , Pi, and extracellular K^+ which occurs with depletion of PCr and glycogen. The first application of the CP model was applied to all-out continuous exercise to see if exercise greater than 90s in duration would stabilize power output and whether that stable power output could be CP once W' has been exhausted. Pilot testing showed that subjects needed to be highly motivated, not be given any time feedback, and showed validity as long as an increasing $\dot{V}O_2$ response attained was greater than 95% $\dot{V}O_2\text{max}$. Remarkably, the $\dot{V}O_2$

response confirms that all out exercise can maximally challenge the aerobic system. CP is the mean power output from the final 30s of the test and is approximately 33% peak power from a GXT. Since $P = \frac{W'}{t} + CP$, if $W' = 0$ and $CP = P$ then when W' is depleted the highest power output is CP.

The mathematical features of CP concept assume: the aerobic system energy component is rate limited, the anaerobic system is capacity limited, and exercise can continue at any power output as long as the energy supply can meet the demands. There are five equivalent equations (three hyperbolic models and two linear models) which are not statistically different. The first model is hyperbolic, but can be linearized by the inverse of time $P = \frac{W'}{t} + CP$ where P = power output, W' = anaerobic working capacity, t = time to exhaustion, and CP = critical power. The second is linear calculating the amount of work done $W = W' + CPt$ where W = total amount of work done. The third linear equation is solved for time $t = \frac{W - W'}{CP}$. The fourth and fifth equation is hyperbolic, $W = \frac{W'P}{P - CP}$ and $P = \frac{CP(W)}{W - W'}$ respectively. These two parameter models of energy supply and demand have been adopted for intermittent exercise. In addition, a three parameter model has been created with the assumption that maximal power output can be a maximal effort, but when W' is depleted then only CP can be recruited. Since a maximal effort during already sustained exercise is lower than if an athlete was fully rested this model is limited between the finite maximal power output and CP. The three-parameter model is listed as $t = \frac{W'}{P - CP} - k$ where k is a temporal asymptote since t is no longer constrained to equal zero.

Practically, the CP concept can assess fitness, prescribe exercise training, and predict performance during high intensity exercise. As far as intermittent exercise, the work interval can

be performed a little higher than CP while the rest interval can be performed at a power output less than CP to ensure partial refilling of W' during recovery. During exercise W' is a function of $(P_w - CP)t_w$ where P_w is the power output during the work interval and t_w is the length of time during the work interval. However, during recovery W' is a function of $(CP - P_r)t_r$ where P_r is the power output during rest and t_r is the length of time during the rest interval.

Fukuda, Kendall, Smith, Dwyer, Stout, 2011

The development of physiological profiles and identification of training needs in NCAA female collegiate rowers using isoperformance curves

The purpose of this study was to develop training strategies for rowers based off of isoperformance curves. Isoperformance curves are a series of linear equations that formulate a minimum performance standard for certain levels of competition in order to separate athletes within a large group. This was achieved by comparing these isoperformance curves with physiological profiles from CV testing. Thirty-five collegiate female rowers performed two CV tests on two separate days. Day one included 400m and 1000m trials with 15mins of rest in between and day two included 600m and 800m trials with the same rest. The linear total distance (L-TD) model was applied plotting total distance versus time for each distance trial. The isoperformance curves also used the L-TD model where total distance was set to 2000m as the y-intercept and time was chosen to represent an acceptable performance at various competition levels as the x-intercept. Then, this model was used to solve for anaerobic working capacity, $W' = 2000m - CVt$, where 2000m represents the usual race distance and t is the total time to complete the race distance at a given velocity. The authors found a highly linear (>0.99) relationship between time and total distance for all subjects. Most importantly, this provides a way for stratifying athletes into junior varsity, varsity, and elite competition levels as well as a

process for team selection. Individually, this yields the ability to provide customized training interventions for each athlete based on the need for more aerobic, anaerobic, or a combination built into periodization schemes.

De Lucas, De Souza, Costa, Grossl, Guglielmo, 2013

Time to exhaustion at and above critical power in trained cyclists: The relationship between heavy and severe intensity domains

The aim of this study was to determine the physiological responses and time to exhaustion at and above CP in trained cyclists. CP delineates a high and low boundary of exercise and represents the highest intensity that is sustainable for a prolonged period of time without eliciting $\dot{V}O_2\text{max}$, hence the lower boundary. Conversely, intensities performed above CP will elicit $\dot{V}O_2\text{max}$. CP and W' can be computed through linear regressions after transforming the hyperbolic relationship into a linear formula by plotting power output versus the inverse of TTE. By showing a greater absolute value compared to other 2-parameter models, the power versus inverse of TTE best estimates CP and is used to investigate physiological responses during CP exercise. The authors hypothesized, given trained cyclists, that their $\dot{V}O_2\text{max}$ would occur at a lower percentage above CP than active people because trained cyclists work at a rate closer to their maximal aerobic power output.

They put 11 trained cyclists ($20 \pm 5\text{yo}$, $71 \pm 12\text{kg}$) through a GXT starting at 100W and increasing 30W/3min until volitional fatigue with $\dot{V}O_2\text{max}$ considered as the highest $\dot{V}O_2$ in a 15s interval. Next, subjects underwent three constant work rates at 95, 100, 110% P_{max} as determined from the GXT in order to determine TTE and calculate CP using power versus the inverse of time. They then performed two sessions, one at CP and one at 5% above CP. All

trials were separated by 24-48hr and subjects refrained from caffeine or strenuous exercise 24hr prior to testing. Blood lactate measures were taken via earlobe at the final 15s of every 3min.

The authors found a correlation between TTE and CP with less time spent above CP (40%) rather than at CP. In addition, when exercise was performed above CP $\dot{V}O_2$ averaged 94% $\dot{V}O_{2max}$ at exhaustion and was not statistically different from the GXT whereas exercise below CP did not reach $\dot{V}O_{2max}$. Also, no differences were found in lactate or HRmax in exercise performed above CP. Since CP is the acceptable delineation between heavy and intense exercise it can be proven useful in prescribing interval training between those domains.

Pettitt, Jamnick, Clark, 2013

3-min All-out Exercise Test for Running

The objective of this study was to examine the efficacy of a 3min all-out running test with a global positioning system (GPS) on competitive distance runners. Theoretically, the anaerobic running distance (running at a speed above CS), will be used up at two and a half min and critical speed (CS) will be the mean speed over the final 30s [$D' = t (S_{150s} - CS)$] where D' is the anaerobic running distance, t is the TTE, and S is the mean speed from the first two and a half min. Fourteen collegiate female distance runners (19 ± 1 yr, 55 ± 4 ml/kg/min) performed a 3min all-out run outdoors on a track. They verified results with a GXT to ensure subjects did not pace themselves over the 3min and 5s test duration.

Successful estimation of outdoor performance occurred within 2% for middle distance (1600m and 5000m) races with the 3min all-out test and two component model equations. Those with greater anaerobic running distances completed races at higher net speeds greater than CS ($r^2 = 0.63-0.99$). Although, 800m times were not accurately predicted the two component equations

could be manipulated for interval prescription based on depleting D' over a longer distance. For instance, interval $t = (D - \text{Interval \%} \cdot D') / CS$ where interval % is given as a fractional percent depletion of D' .

Broxterman, Ade, Poole, Harms, Barstow, 2013

A single test for the determination of parameters of the speed-time relationship for running

The purpose of this study was to determine if a single all-out test can accurately measure CS and D' . The authors looked specifically at whether the final 30s of a single test (end test speed) and D' would differ significantly from the traditional CS protocol. Seven healthy subjects (4 men and 3 women, 25.3 ± 3.4 yr) visited the human performance lab eight times separated by at least 24hrs. Subjects began with an incremental GXT on a treadmill to determine $\dot{V}O_{2\max}$ and the speed at $\dot{V}O_{2\max}$ (Speak). Then subjects performed three separate constant speed runs (at 90-120% Speak) to exhaustion to determine the speed-time relationship. The results were computed into a two-parameter linear speed versus the inverse of time model, $S = \frac{D'}{t} + CS$, to determine CS and D' . Subjects then performed two validation trials at constant speeds slightly above and below their CS. Finally, subjects performed a 3min all-out test to determine end speed (the speed during the final 30s) and the distance above end test speed. The run slightly above CS reached $\dot{V}O_{2\text{peak}}$ values similar to that of the incremental GXT to exhaustion whereas the $\dot{V}O_{2\text{peak}}$ slightly below CS did not. They found that the 3min test accurately predicted CS from the speed versus 1/time model and that CS was shown to occur in close proximity to lactate steady state. The 3min end speed was not significantly different from CS and the distance covered above CS was not significantly different from D' .

Metabolic requirements/Energy systems

Gaitanos, Williams, Boobis, Brooks, 1993

Human muscle metabolism during intermittent maximal exercise

The aim of this study was to describe the metabolic changes in subjects performing intermittent exercise of maximal intensity to examine the energy contribution made by PCr degradation and glycolysis. Previously, studies have demonstrated that short bouts of exercise over time would reduce PCr and place a greater demand on glycogenolysis to provide ATP. Eight males (26.7 ± 8.4 yr) performed 10 6s sprints with 30s rest on a cycle ergometer from a stationary position. Researchers measured their blood lactate after the first, fifth, ninth, and tenth sprint as well as 3min, 5min, and 10min post exercise. In addition, muscle biopsies from the vastus lateralis were taken at rest, after the first sprint, 10s before the tenth sprint on one leg, and immediately after the tenth sprint on the opposite leg.

Peak Power fell by 33.4% after the tenth sprints and 47.5% of that fall dropped within the first five sprints. There was a strong correlation between lactate and total work done over the first five sprints ($r = 0.88$, $p < 0.05$, $n = 6$) as there was a 15-fold increase in blood lactate after five sprints. However, blood lactate did appear to plateau after 9 sprints as it did not change after 10min post exercise. The subjects that dropped the greatest in mean power after 10 sprints tended to have the largest change in lactate and pH post exercise even though a decrease in H^+ ions occurred at a faster rate than a decrease in lactate post exercise.

As far as the metabolites are concerned, PCr and ATP dropped 57% and 13%, respectively, after the first sprint and by the last sprint PCr and ATP dropped 51% and 32% of resting values, respectively. Similarly, glycogen dropped 14% after the first sprint and 30% by

the last sprint. The rate of ATP production went from 89% at the first sprint to 32% at the tenth sprint. Initially, PCr degradation accounted for about one half (49.6%) of the ATP resynthesis from anaerobic stores while the rest predominantly came from glycolysis (44.1%). During the final sprint, PCr accounted for 80% of the total ATP production. Most glycogen was metabolized aerobically because the highest rates of glycogen degradation in the first sprint accumulated more lactate in muscle and also had the greatest ATP production rates from anaerobic stores. Those individuals that had the greatest fall in mean power output over the ten sprints also had the greatest glycolytic rate during the first sprint ($r = 0.893$, $p < 0.01$, $n = 7$) and those who performed more work in the first sprint also performed more work in the tenth sprint ($r = 0.851$, $p < 0.05$, $n = 7$).

The average first sprint derived energy mainly from PCr and anaerobic glycolysis, but by the last sprint energy was derived from PCr and oxidative metabolism. Hence, a greater shift towards aerobic metabolism in the later sprints may have occurred due to a decreased anaerobic energy yield. This may have occurred because there was no apparent accumulation of lactate and a leveling off of average power output.

Green, 1994

A definition and systems view of anaerobic capacity

The goal of this paper was to define and describe anaerobic capacity and its related terms as well as provide an overview of the metabolic systems in which it occurs. Historically, it was not until the 1960s where anaerobic capacity was used to describe a finite source of energy, yet it was not entirely clear at this point in time. Anaerobic refers to the metabolic processes which resynthesize ATP without oxygen while the capacity means a potential amount that can be

contained. Therefore, anaerobic capacity refers to the total amount of energy or work irrespective of time. Although, there must be a clear distinction between chemical energy and work where chemical energy remains in the form of ATP and work refers to the mechanical work done during exercise. Anaerobic capacity can be estimated by assuming ATP yield is associated with the accumulation of anaerobic by-products (e.g. lactate) or a reduction in substrate supply (e.g. PCr). Since work output can be influenced by the ATP supply or oxidative metabolism, mechanical work will reflect anaerobic ATP supply and the oxidative sources of ATP contribution, as well various factors involved in the transferal of chemical energy to mechanical work done. Now, anaerobic capacity can be defined as the maximal amount of ATP resynthesized via anaerobic metabolism during specific short-term maximal exercise, providing an anaerobic potential applied to exercise. Similarly, anaerobic work capacity is defined as the total amount of work done during exhaustive exercise that elicits a near maximal anaerobic ATP yield, provided that this ATP yield exceeds that from oxidative metabolism.

Anaerobic capacity can increase via two physiological states. First, given the rate of lactate production involved in high intensity exercise, increasing the acid-base status of the working muscles could increase anaerobic capacity. Second, considering lactate producing muscle mass and accumulating H⁺ concentration, lactate oxidation could play a role in factoring anaerobic capacity. Increasing oxidative capacity can more efficiently remove lactate from circulation and if all other determinants remain constant, an increase in anaerobic capacity of skeletal muscle may occur.

Muscle phosphocreatine repletion following single and repeated short sprint efforts.

The purpose of this study was to examine the repletion of PCr after a single 6s sprint versus five 6s sprints with the hypothesis that less PCr availability will be apparent following five 6s sprints because of a slower rate of replenishment. PCr stores are severely depleted after 5-7s of maximal exercise and to make up for the energy yield glycolysis will provide the bulk of ATP if exercise continues further. Glycolysis also becomes increasingly important when PCr cannot replenish during repeated sprints. Short sprints result in H⁺ accumulation, a drop in pH, and an increase in lactate. As a result, PCr resynthesis becomes inhibited post-exercise. Initially, PCr replenishment is an oxygen dependent process, but with continuous exercise over 3min it is limited by the change in intramuscular pH. While PCr utilization will be less in a 10s sprint compared to a 30s sprint, the rate of PCr resynthesis will be different as glycolytic contribution in a 30s sprint will result in greater H⁺ concentration and lower pH. For instance, a trained sprinter will be better able to utilize their PCr stores over a single 5-7s sprint.

The researchers utilized two different groups for the single and multiple sprint protocols. The single sprint sample was composed of seven volleyball athletes or experienced track sprinters (26 ± 4yr) and the multiple sprint sample was composed of eight rugby and volleyball athletes (24 ± 4yr). The subjects performed a warm-up, a couple practice starts, a 5min rest, and then sprinted a single 6s sprint or five 6s sprints with 24s of recovery. Afterwards, muscle biopsies were conducted after 10s, 30s, and 3min post.

After 10s, 30s, and 3min of a single maximal 6s sprint, PCr was 55%, 69%, and 90% of baseline values whereas after five 6s maximal sprints, PCr dropped to 27%, 45%, and 84% of

baseline values, respectively. In addition, ATP fell 16% in the single sprint with a 6-fold increase in lactate compared to a 34% drop in ATP and a 14-fold increase in lactate after five sprints. The amount of work performed was correlated to 10s post lactate values as well as a change in lactate, however PCr levels did not correlate with lactate at 30s or 3min post exercise. This study demonstrated that PCr repletion was significantly higher in the multiple sprints and that full repletion of PCr takes greater than 3min. There was also a correlation of lower lactate levels associated with higher PCr concentrations. Again, both a lower ATP concentration and a decrease in intramuscular pH are thought to slow recovery of PCr after exercise.

In conclusion, PCr can make a considerable contribution to ATP synthesis for further sprints to occur, however five 6s sprints with 24s rest reduced PCr stores to 45% of resting levels decreasing PCr potential for ATP resynthesis in further sprints. In turn, more ATP must come from glycolytic or oxidative pathways. Therefore, sprint performance will decline as ATP resynthesis occurs at a slower rate without PCr availability for energy metabolism. Since full recovery of PCr takes longer than 3min the rate of repletion is not slower after multiple sprints versus a single sprint. Although, full repletion is likely to take longer after repeated sprints due to a greater PCr depletion which causes replenishment to occur at a lower PCr level rather than a slower rate of repletion.

McMahon, Jenkins, 2002

Factors affecting the rate of phosphocreatine resynthesis following intense exercise

The purpose of this review article was to examine the factors affecting the rate of PCr resynthesis following intense exercise. Athletes can benefit from an increased rate of PCr resynthesis during interval exercise because of brief rest periods. In particular, aerobic power

should be able to increase the rate of PCr resynthesis, especially compared to sedentary counterparts.

Energy production is derived from hydrolysis of $\text{ATP} \rightarrow \text{ADP} + \text{P}_i$ and three energy systems contribute to ATP resynthesis. In particular, PCr breakdown provides a buffer to potential decreases in ATP during exercise. PCr also rephosphorylates ADP, re-utilizing ATP for contraction, and leading to an increase in P_i which activates the key glycolytic enzyme phosphofructokinase (PFK). However, the energy yield of PCr can drop to less than 40% of resting values within 10s of intense exercise. On the other hand, glycolysis is self-regulated during very high intensity exercise as H^+ dissociate from end product lactic acid and potentially impair contraction due to interference with contractile proteins and inhibition of key enzymes. Lastly, the oxidative system operates at full potential around 45s and it yields the slowest rate of ATP turnover.

During prolonged exercise fatigue can be contributed by thermal stress, substrate depletion, and possibly a reduction in PCr caused by ADP phosphorylation as well as an increase in H^+ concentration. PCr is resynthesized by ATP production via oxidative phosphorylation only. Specifically, the initial rate at which PCr is recovered is by mitochondrial ATP resynthesis and free from inhibition by H^+ . However, later stages inhibit PCr resynthesis by increasing H^+ concentration producing a lower pH. PCr recovery can be graphically displayed as a mono-exponential function when pH is not significantly reduced. Yet, it becomes more complex when contraction is intense and pH remains lowered when ADP returns to resting levels.

Glaister, 2005

Multiple sprint work: Physiological responses, mechanisms of fatigue, and the influence of aerobic fitness

The basis for this review was to explore the link between aerobic fitness and fatigue during multiple sprint work. Many activity patterns in sports consist of repeated sprints less than 6s with less than 60s rest. Analysis of field sports reported a mean duration of high intensity efforts lasting 4-7s. In general, high intensity efforts last 5-10s depending on position and ability with a 1:1–1:5 work-to-rest ratio. During a 5-6s sprint, ATP is resynthesized by PCr degradation, glycolysis, and oxidative phosphorylation (<10%). During recovery, within multiple sprints, oxygen is elevated in order to restore homeostasis by replenishing tissue oxygen stores, resynthesis of PCr, metabolism of lactate, and removal of Pi. When rest periods are short $\dot{V}O_2$ remains high prior to subsequent sprints and the aerobic system contributes to ATP resynthesis, but when rest is insufficient performance will suffer because homeostasis is not achieved. The average exercise intensity response of intermittent exercise is similar to continuous exercise and current lab based practices examine sprints less than 6s with less than 60s rest to assess physiological responses to this activity.

ATP within muscle human body stores is approximately 20-25mmol/kg dry muscle (dm) and peak turnover rates occur at 15mmol/kg dm, which is enough fuel for 1-2s of maximal work. As ATP becomes depleted it is resynthesized by various metabolic processes such as PCr, glycolysis, and oxidative phosphorylation. First, ATP is resynthesized by the reaction between PCr and ADP catalyzed by creatine kinase (CK). In addition, intramuscular stores of PCr are 80mmol/kg dry muscle and can be severely depleted within 10s. Also, PCr has the most predominant ATP turnover rate at 9mmol ATP/kg dm/s. Secondly, glycolysis breaks down

muscle glycogen to ATP and lactate with peak ATP production rates equal to 6-9mmol ATP/kg dm/s. Third, aerobic metabolism contributes very little to the first 6s maximal sprint at approximately 9% of the total energy production. During maximal work, aerobic ATP resynthesis is primarily accomplished via glucose oxidation. Aerobic metabolism has the slowest ATP turnover rate at 1.32mmol ATP/kg dm/s. Lastly, when intensity is high and ADP molecules cannot be resynthesized from PCr, glycolysis, and oxidative phosphorylation it can be resynthesized from pairs of ADP molecules and catalyzed by adenylate kinase. Overall, the integration of all these metabolic processes work together to produce an ATP turnover of 15mmol/kg dm/s.

During 5-6s sprints PCr degradation is about 50% of the total anaerobic ATP oversight, but it is dependent on its storage recovery during the rest bouts. PCr is sensitive to oxygen availability and resynthesis is attained exclusively by ATP resynthesis and initially unaffected by any drop in pH. After submaximal work with minimal change to pH, PCr will follow a mono-exponential pattern of resynthesis, but following maximal work, PCr will follow a bi-exponential pattern of resynthesis. Together, PCr and glycolysis maintain an ATP turnover rate of 11-14mmolATP/kg dm/s. During maximal intermittent work, glycolysis is inhibited due to the progressive changes in the metabolic environment. For example, over 10 sprints glycolysis accounted for 44% of ATP provision during the first sprint and dropped to 0-16% during the tenth sprint. With the increase in lactate and H⁺ concentrations, pH returns to resting levels in a mono-exponential pattern of resynthesis with a half-time of approximately 9min. The depletion of glycogen stores, drop in pH, H⁺ accumulation and a small influence of cytosolic citrate inhibiting PFK may cause the significant drop in glycolysis contribution to ATP resynthesis.

Aerobically if the work bout is a few seconds and since there is a delay in $\dot{V}O_2$ from the working muscles, the oxygen bound to myoglobin may be utilized for the initial oxygen demand of exercise. Myoglobin storage is 2mmol O_2 /kg dm and is fully replenished at a rapid rate within 20s following the cessation of exercise and does not appear to be a limiting factor during repeated sprints. Again, during rest $\dot{V}O_2$ remains elevated to replenish myoglobin stores, resynthesize PCr, metabolize lactate, and remove Pi. However, if subsequent sprints are performed before $\dot{V}O_2$ returns to baseline levels then the $\dot{V}O_2$ of those sprints will also be elevated. The reason this occurs is from the pH response which increases the Bohr shift of the oxygen-haemoglobin dissociation curve, increases vasodilation to the muscles, increase recruitment of motor units, and increase pyruvate dehydrogenase.

Fatigue during multiple sprint work can be masked by a potentiation effect in the first few sprints which is mechanistically unknown. Mechanisms of fatigue include, the lack of available ATP for actin-myosin binding, Na^+/K^+ pumping, and Ca^{+2} uptake by the sarcoplasm reticulum and inhibition of ATP from metabolic by-products which alters excitation-contraction coupling from the action potential to Ca^{+2} release from the sarcoplasm reticulum.

Since energy utilization during maximal sprints is primarily maintained by PCr and glycolysis, deficiencies in energy production are likely to be associated with limitations in anaerobic metabolism. In specific, PCr availability is likely the limiting factor in the development of fatigue during multiple sprint work whereas glycogen is unlikely to be a major factor in maintaining ATP. Glycogen availability has little influence in maintaining high power output during short brief maximal intermittent work, but the drop in pH with anaerobic glycolysis causes fatigue. Furthermore, a drop in pH has a strong correlation with a decrease in

power output. Currently, the major cause for muscle fatigue in high intensity exercise is the accumulation of Pi by inhibiting Ca⁺² release from the sarcoplasm reticulum.

Therefore, the link between oxygen and PCr recovery is likely to influence the magnitude of PCr contribution to ATP turnover during each sprint because oxygen influences Pi accumulation. A higher $\dot{V}O_{2max}$ could enhance PCr recovery as it has been reported in endurance athletes. In hyperoxic environments, repeated sprints were associated with a reduced accumulation of anaerobic metabolites due to enhanced $\dot{V}O_2$ kinetics at the onset of exercise. Conversely, hypoxic environments were associated with increased blood lactate levels, decreased $\dot{V}O_2$, and an increased rate of fatigue influenced by the magnitude of aerobic contribution to ATP resynthesis during the work bouts and the rate of PCr resynthesis during the rest bouts.

Mathematical Modeling

Moritani, Nagata, DeVries, Muro, 1981

Critical power as a measure of physical work capacity and anaerobic threshold

The scope of this study was to evaluate if the CP concept from Monod and Scherrer could be extended to whole body exercise and whether it might provide information about anaerobic threshold and $\dot{V}O_{2max}$. The relationship between maximal work and the maximal time, before local muscular exhaustion, can be expressed as $W_{lim} = a + b (T_{lim})$, where a is the maximal work from an energy reserve or W' , b is the maximal energy reconstitution rate or CP, W_{lim} is the total amount of work done, and T_{lim} is the total amount of time work was performed before exhaustion. First, subjects performed a GXT. Next, eight male and eight female college students underwent exercise tests at four different, but constant power outputs on a bicycle ergometer until fatigue. Specifically chosen power outputs for men and women were performed

in order to elicit exhaustion earlier or later. CP was determined via total work performed and the time in which this work was completed until the initial power level could no longer be maintained. Now the power of work can be defined as $P = W_{lim}/T_{lim}$ and the inverse can be $W_{lim} = P \times T_{lim}$. W_{lim} was obtained from three different power outputs as a function of T_{lim} and plotted on the same graph where the slope (b) determined CP and the y-intercept (a) determined W' . Additionally, two subjects underwent the same CP procedures with oxygen consumption testing to validate CP.

According to the relationship between W_{lim} and T_{lim} , regression expressed linearity with goodness of fit scores ranging from 0.982 to 0.998 ($p < 0.01$). CP was expressed as $\dot{V}O_2$ equivalents by solving for $\dot{V}O_2$ at CP using linear regression and relating $\dot{V}O_2$ and power obtained during $\dot{V}O_2$ max testing. Alternatively, there was a correlation observed between $\dot{V}O_2$ at anaerobic threshold and CP ($r=0.907$, $p<0.01$) and $\dot{V}O_2$ at anaerobic threshold and $\dot{V}O_2$ at CP ($r=0.927$, $p<0.01$). Moreover, correlations existed between $\dot{V}O_2$ max and CP ($r = 0.87$, $p < 0.01$) and $\dot{V}O_2$ max and $\dot{V}O_2$ at CP ($r = 0.919$, $p < 0.01$). However, the sum of CP (b) and W' (a) was more so correlated with $\dot{V}O_2$ max ($r = 0.956$, $p < 0.01$). Hypoxia testing found that lowering the oxygen consumption reduced the slope of the linear equation (CP), but proves to affect W' very little showing that CP is an oxygen dependent process whereas W' represents PCr and muscle glycogen stores. Therefore, CP is given as a rate of energy supply whose magnitude determines maximal power at which muscle can work without fatigue.

The y-intercept of the critical power function as a measure of anaerobic work capacity

The aim of this study was to prove the y-intercept as a valid representation of W' . This was discovered through the relationship between the y-intercept (derived as a function of CP) and total work (TW), blood lactate, and post-exercise blood pH from five 1min exercise bouts. Nine moderately active males (18.8 ± 1.2 yr) performed a GXT, three CP tests, and one interval exercise testing bout. The CP tests were performed at three different intensities (300W, 350W, 400W) until fatigue or less than 60rpm for 3s. The TTE and TW were recorded at each trial. The interval testing assessed W' with five 1min maximal bouts against a resistance of 0.075N/kg with 5min passive rest seated on the cycle ergometer. The accumulated work over the five bouts was calculated taking into account rpm, applied resistance, and work done to rotate the flywheel through one complete cycle. Blood lactate measurements were taken 4-5min into passive recovery after each bout and pH was taken pre and within 90s after the final exercise bout. Their results indicated that $\dot{V}O_2\text{max}$ and CP were not significantly correlated ($r = 0.11$) despite typically being associated with endurance ability. On the other hand, linear coefficients between the TTE and TW for each CP test were greater than 0.99 for each subject showing their linear relationship. The low correlation between W' and CP ($r = -0.11$; $p > 0.05$) demonstrates the independent nature between the aerobic and anaerobic components. Subjects were in a state of full exhaustion at the end of the final exercise bout. The y-intercept was significantly correlated with TW ($r = 0.92$; $p < 0.01$) accumulated over the five 1min exercise bouts and blood pH ($r = 0.92$; $p < 0.01$) post-exercise. Post-exercise pH was correlated with $\dot{V}O_2\text{max}$ ($r = 0.84$; $p < 0.05$) showing that individuals with a higher $\dot{V}O_2\text{max}$ may be able to sustain low pH levels by deriving greater ATP from aerobic metabolism.

Overall, results establish that as exercise increases aerobic involvement increases and that aerobic metabolism can make up to 28% of the total ATP provision during a 30s sprint. Lactate levels during interval bouts were at least as demanding as a Wingate test (13.9 ± 1 mmol/L). Results imply that individuals with a high y-intercept were able to do more work during interval bouts compared with lower values. In conclusion, the y-intercept does reflect W' and is a useful indicator in performing intermittent high intensity work

Green, Dawson, Goodman, Carey, 1994

Y-intercept of the maximal work-duration relationship and anaerobic capacity in cyclists

The purpose of this study was to examine the concurrent validity of the y-intercept, based on the work-time relationship, as it represents W' . Ten well trained male cyclists (26 ± 9 yr) performed a lactate threshold test, a GXT, and three exhausting cycle sessions on separate occasions. Power outputs for each exhausting cycle session were 104%, 108%, 113% $\dot{V}O_{2peak}$ and the TW and TTE (T_{lim}) were measured for each subject. The work (W_{lim}) was calculated as the product of the mean power output and the total time for each respective session. Then the three W_{lim} and T_{lim} were plotted and described as the function of $W_{lim} = a + b (T_{lim})$, where a is the y-intercept and b is the CP. However, in order to maximize anaerobic ATP production an alternative method was conducted that incorporated the additional work subjects completed when cadence declined, but power output was still greater than $\dot{V}O_{2peak}$. Additionally, muscle biopsies from the vastus lateralis and lactate measurements were analyzed pre and post exercise. The y-intercept appeared to underestimate W' as these values lie in a lower range of the previous literature. Although, an alternative method produced a y-intercept 27% greater than the original method and CP was lower. A larger W' is associated with a larger decrease in ATP during fatiguing exercise and a larger decrease in ATP is shown to correspond to fast twitch muscle

fibers which are better suited for high intensity work compared to slow twitch muscle fibers. Through this study it can be implied that the subjects who exhibited a greater decline in ATP also recruited a higher percentage of fast twitch muscle fibers, further supporting the y-intercept as an estimate for W' since W' is associated with an increase in the recruitment of fast twitch fibers critical in developing W' . As for untrained subjects, the reliability of the y-intercept varies from $r = 0.67$ to $r = 0.97$. Unfortunately, the reliability of y-intercept was not determined in this study.

Bull, Housh, Johnson, Perry, 2000

Effect of mathematical modeling on the estimation of critical power

The aim of this study was to examine the CP estimates from the five mathematical models and analyze the time spent at CP during the lowest estimate for each model. Nine male subjects (25 ± 3 yr) volunteered for this study, but were not highly experienced cyclists. Each subject underwent eight or nine trials with ≥ 24 hr rest in between trials. First, subjects performed a GXT to determine peak power and peak heart rate (HR_{peak}). Next, subjects performed five to six trials randomly ordered at power outputs ranging from 130W below peak power to 50W above peak power while maintaining 60rpm for the estimation of CP. The first five predictive trials utilized power outputs between 50W above and below peak power and if none of the trials lasted 10min than an additional estimated trial was given to last at least 10min. Time stopped when the subject could no longer maintain a cadence of 60rpm. Five linear regression models were used to estimate CP. The model that provided the lowest estimate of CP was used to determine the power output for the final two trials at CP.

The first of the five models was L-TW which was based on the regression of total work and time to exhaustion (t), where $TW = W' + CPt$ utilizing $y = a + bx$ of a line. The second model utilized two equations, $TW = Pt$ and $TW = W' + CPt$, producing the linear power (L-P) model as $P = W' (1/t) + CP$. By giving the inverse of time ($1/t$) one can transform the hyperbolic relationship into a linear relationship. The third model was based on the power-time relationship and is shown as the nonlinear-2 model, where $t = W' / (P-CP)$. The fourth model is nonlinear and involves maximal instantaneous power (P_{max}) in order to overcome the assumption in the nonlinear-2 model that as time approaches zero power is infinite. This allows for a time asymptote below the x-axis, giving power an x-intercept, which is made possible by parameter k added into the nonlinear-2 model. In turn, the nonlinear-3 model is $t = (W' / (P-CP)) - (W' / (P_{max}-CP))$. The fifth model is an exponential model (EXP) where $P = CP + (P_{max} - CP)\exp^{-t/\tau}$ and τ is an undefined constant. This model does provide P_{max} to overcome the previous assumption; however, it does not provide an estimate of W' .

The nonlinear-3 model resulted in the lowest CP estimate for each subject and was produced significantly lower CP estimates as compared with all other models. CP estimates ranged from r^2 values of 0.847 to 1.0 (L-TW: $r^2 = 0.997-1.0$; SE = 1-5W, L-P: $r^2 = 0.847-0.991$; SE = 6-15W, nonlinear-2: $r^2 = 0.894-1.0$; SE = 0-8W, nonlinear-3: $r^2 = 0.937-1.0$; SE = 0-39W, EXP: $r^2 = 0.904-0.996$; SE = 5-20W) Specifically, the L-P model resulted in the lowest r^2 values possibly because of the conversion from hyperbolic to linear relationships. Also, evidence validating CP may conflict when derived from mathematical models and compared to fatigue threshold parameters. For instance, peak power and $\dot{V}O_{2max}$ at CP were not different from ventilatory threshold (V_L) (from L-TW and nonlinear-3 models). In addition, power output at CP was greater than V_L (from L-P model), and blood lactate at CP was greater than onset of

blood lactate accumulation (OBLA) (from L-TW model). Only two of the nine subjects did not complete 60min in either of the CP trials. HR at the end of these CP trials was 91-97%HR_{peak} and the mean RPE was 19 for those who completed the trials.

Housh, Cramer, Bull, Johnson, Housh, 2001

The effect of mathematical modeling on critical velocity

The purpose of this study was to examine the effects of the five mathematical models on critical velocity (CV) estimates and corresponding oxygen consumption ($\dot{V}O_2$), HR, and plasma lactate values. Ten male subjects who regularly exercised, but not highly trained, performed four CV test to failure based on their fitness level. First, subjects underwent a GXT to determine $\dot{V}O_{2max}$ then performed four randomly ordered treadmill tests until exhaustion on separate days at a selected pace that would induce fatigue between 2 and 12min. Two linear models (Linear total distance (L-TD), linear velocity (L-V) and three nonlinear models (nonlinear-2, nonlinear-3, exponential), based on cycle ergometry from previous literature, were used to estimate CV. CV was estimated for L-TD ($r^2 = 0.99-1.0$, SE = 0.1-0.5km/hr), L-V ($r^2 = 0.94-.99$, SE = 0.1-0.4km/hr), nonlinear-2 ($r^2 = 0.94-0.99$, SE = 0.1-1.4km/hr), nonlinear-3 ($r^2 = 0.95-0.99$, SE = 0.5-5.8km/hr), EXP ($r^2 = 0.82-0.98$, SE = 0.3-1.7km/hr). The nonlinear-3 model produced significantly lower mean CV estimates as compared with all other models and resulted in the lowest estimates of CV for each subject. Oppositely, the EXP model resulted in the highest mean estimates of CV and the highest value for each subject. Moreover, the nonlinear-3 model produced the highest ranges of W' . Unfortunately, the transformation of nonlinear data into linear data produces parameter estimates different from nonlinear analysis. The L-TD, L-V, and nonlinear-2 models results in similar mean CV estimates with differences by only 0.2km/hr.

These three models appeared to overestimate a true fatigue threshold as HR, $\dot{V}O_2$, and lactate corresponded to submaximal levels.

Skiba, Chidnok, Vanhatalo, Jones, 2012

Modeling the expenditure and reconstitution of work capacity above critical power

The focus of this study was to develop a mathematical model to represent the dynamic state of W' during severe intermittent exercise, investigate the possible link between $\dot{V}O_2$ kinetics and the depletion of W' , and to explore if this model will be useful in a real world cycling competition. Seven healthy recreationally active, but not highly trained individuals performed a GXT, a 3min all-out test to determine CP and W' , and four constant work rate intermittent trials to exhaustion. The intermittent trials were composed of 60s of work, at a power output designed to elicit exhaustion in 6min with multiple recovery intervals (light, moderate, heavy, and severe intensity). The authors utilized a continuous equation to predict the remaining W' at any given time until W' was fully depleted and exhaustion occurred. The work time constants were inversely correlated with CP during the moderate rest period ($r^2 = 0.64$, $p = 0.03$) and strong trends were shown in the light and heavy intensity rest periods ($r^2 = 0.53$, $p = 0.06$ and $r^2 = 0.48$, $p = 0.08$ respectively). In addition, the work time constants versus the derived time constants were shown to be best fit by exponential regression yielding a close relationship with light, moderate, and heavy rest periods. Furthermore, the modelled depletion of W' was strongly related to a rise in $\dot{V}O_2$, above baseline, during each interval within the severe intensity domain ($r^2 = 0.82-0.96$, $p < 0.0002-0.0049$) showing there was a greater change in $\dot{V}O_2$ with increasingly harder recovery periods. Researchers then retrospectively analyzed power meter records from an amateur cyclist during a road race and found that their modelled equation accurately predicted W' . The authors concluded two compartments, which represent

simultaneously activated type I and type II fiber pools, supply the energy for W' . The absolute contribution of energy coming from each compartment is different and is delivered at different rates during recovery. Lastly, the sum contribution of each compartment must equal W' .

Repeated Sprint Ability

Fitzsimmons, Dawson, Ward, Wilkinson, 1993

Cycling and running tests of repeated spring ability

The purpose of this study was to develop a reliable laboratory and field RSA test for greater quality assessment of repeated sprints. Participants, in the first phase, went through three days of testing on the cycle ergometer and sprinting on a grass oval separately. The first day established their maximal peak sprint times and total work utilizing 2x6s sprints. The second day consisted of 6x6s cycle sprints or 6x40m running sprints with 24s rest. The final day repeated the RSA procedures from day two. Lactate measurements were drawn 1, 3, 5, and 7min post RSA on day two. This three day process was then repeated with another group of individuals without lactate measurements. Test scores were analyzed by the absolute total time and the total work done in the six sprints as well as relative percent decrement over each sprint effort. Repeated repetition test scores within each test for each individual were highly correlated $r = 0.81-0.97$. In the first phase, each sprint showed consistent and significant decrements in performance; however greater increases in fatigue were shown on the cycle. Decrements in fatigue imply a depletion of the anaerobic working stores and the higher values in cycling could be due to local muscular fatigue. The greatest work achieved in the first cycling sprint was highly correlated with the greatest overall total work and least amount of total time ($r = 0.916$, $p < 0.01$). No significant differences between absolute and relative performance scores in the

second and third day. In the second phase, each cycle and running RSA were correlated and showed consistency and validation. Likewise, lactate measurements were consistent with game type situations. The RSA proves to be consistent and a valid specific fitness assessment for coaches and professionals alike.

Glaister, Stone, Stewart, Hughes, Moir, 2005

The influence of recovery duration on multiple sprint cycling performance

The aim of this study was to examine the influence of two different recovery durations on various performance and physiological markers. They put 25 physically active men, most of who were currently involved in intermittent sports, through two maximal cycling sprint protocols involving 20x5s sprints with either 10s or 30s of rest. Participants were instructed to refrain from vigorous exercise the day before testing and to maintain their normal diet. The subjects pedaled against a resistance of 0.75kg body weight for each protocol and were monitored for heart rate, lactate (every 10 sprints and 5min post), $\dot{V}O_2$, and rate of perceived exertion (RPE). There were no significant differences in power output, but fatigue between rest periods was 14.1-18.2% difference between protocols. Mean $\dot{V}O_2$ was not statistically difference between protocols, but there was a 15.9% difference during recovery. Likewise, mean HR was 10.1% higher with 10s of rest as opposed to 30s of rest, respiratory exchange ratio (RER) was 6.6% lower, and lactate levels were significantly lower after 10 sprints, 20 sprints, and 5min post exercise with 30s of rest. The longer rest duration protocol allowed for greater recovery possibly via PCr contribution to ATP resynthesis and enhanced Pi removal. There was no change in $\dot{V}O_2$ through both protocols, but there were changes in RPE likely due to VCO_2 as a result from H^+ ion buffering.

Billaut, Basset, 2007

Effect of different recovery patterns on repeated sprint ability and neuromuscular responses

The aim of this study was to examine muscle fatigue processes in RSA exercise via manipulated recovery patterns. Thirteen healthy male students (23 ± 3.0 yr) with competitive sport experience performed repeated 6s sprint sessions on three separate occasions 48hrs apart. Subjects completed ten sprints on a cycle ergometer with three different recovery patterns including: constant (30s), increasing (10s, 15s, 20s, etc.), or decreasing (50s, 45s, 40s, etc.). Each sprint was initiated with one leg at a 45° angle to the vertical axis. They found that the first sprint generated the highest peak power output in each recovery pattern. Meanwhile, decreases in peak power were displayed from the eighth to the tenth sprint in both constant and decreasing recovery patterns whereas decrements from the third to the ninth sprint were seen in the increasing recovery pattern. The TW performed was significantly affected by the recovery pattern as the increasing pattern had the lowest TW and the decreasing pattern had the highest TW. Decrements in peak and mean power were different between each recovery pattern. It is possible that the decrements observed in the increasing recovery pattern were due to insufficient PCr resynthesis, inhibition of contractile activity via lowered muscle pH, or a change in ionic concentrations. However, this was least likely the case in the constant or decreasing patterns. Hence, recovery period between sprints is important and small differences in rest time could have significant effects on performance outcomes. Further, RSA activity may become impaired when a critically short rest period is used. Overall, the fatigue process in RSA exercise may be differentially affected by the recovery pattern imposed.

Faster oxygen uptake kinetics during recovery is related to better repeated sprint ability

The purpose of this study was to analyze the relationship between performance decrements and $\dot{V}O_2$ kinetics during rest in RSA. Ten male amateur soccer players (23.2 ± 3.8 yr) performed a GXT, two runs till exhaustion, and a RSA. The GXT measured $\dot{V}O_{2peak}$ and maximum aerobic speed (MAS), the two runs till exhaustion were conducted at 120% MAS and followed by 6min rest, and the RSA included seven 30m sprints on an indoor track with 20s active rest. The percent decrement score (%DS) was calculated as, $\%DS = [100 \times \text{total sprint } t / \text{ideal sprint } t] - 100$, where total sprint time was the sum of the seven sprints and the ideal sprint time was the fastest sprint during the RSA multiplied by the number of sprints. On the other hand, $\dot{V}O_2$ kinetics was measured during the 6min rest after the two exhaustive runs where the subjects sat in a chair with breath-by-breath O_2 collection. The researchers found no significant differences between either exhaustive run in TTE. Likewise, total sprint time did not significantly correlate with %DS ($r = 0.16$), but %DS did correlate with $\dot{V}O_{2peak}$ ($r = -0.83$). The study confirmed that individuals with higher $\dot{V}O_2$ kinetics during recovery observed smaller %DS during RSA ($r = 0.85$). The reason oxygen consumption remains elevated during recovery is to replenish myoglobin stores, resynthesize ATP and PCr, and remove lactate. Significantly reduced sprint performance was noted during the RSA implying that the rest periods were not long enough to fully recover. During recovery the body is suffering from low PCr stores, an accumulation of K^+ in the muscle interstitium and P_i . PCr resynthesis appears to be the most important factor in recovery and a faster $\dot{V}O_2$ decline during subsequent sprints is associated with a quicker recovery, a faster rate of PCr resynthesis, and a smaller decrement in performance.

Morin, Dupuy, Samozino, 2011

Performance and fatigue during repeated sprints: what is the appropriate sprint dose?

The aim of this study was to quantify the variability in the amplitude of performance decline over an individualized sprint dosage. Fifteen active males subjects, majority of who perform repeated sprints as part of their training regimen regularly. Subjects were told to perform 6s sprints interspersed with 24s rest on a cycle ergometer until they reached a fatigue index (FI) or 20 sprints. The resistance load on the cycle ergometer for the RSA protocol was set to 0.75N/kg and each sprint started from a standardized position with the preferred leg at a 45 degree angle. FI was calculated as a percent difference between ideal power and actual power. This involved the sum of the power outputs from the first sprint to the nth sprints over the highest power output performed during n sprints multiplied by n number of sprints. The target output decrement was chosen at 10% as it is common with previous literature and exhaustion occurred when subjects performed two consecutive bouts above this. The sprint at which this occurred was compared with the tenth sprint for variability. The individualized sprint dosage lowered the intersubject variability in FI. The CV for the FI at the tenth sprint was 47.3% versus 10.8% at the nth sprint. Although significantly higher, the FI at n sprints was $11.2 \pm 1.2\%$ which is close to the 10% FI. This proves valuable for individually prescribing a fatigue stimulus rather than using a fixed number of sprints for an entire group or team.

Turner, Stewart, 2013

Repeated sprint ability

The purpose of this review was to describe the most important physiological variables for improving RSA and how to report RSA results. RSA describes an athlete's ability to recover

and maintain maximal effort during subsequent sprints. It is appropriately measured via interval training and should resemble an appropriate work-to-rest ratio. Power is the rate at which ATP is used as fuel and sprint speed relates to depleting large amounts of high energy phosphates quickly. Various energy systems work together to regenerate ATP, but the contribution of each is dependent on the duration and intensity of the rest period. Specifically, PCr produces ATP at a rate of 9mmol/kg/s, anaerobic glycolysis produces ATP at a rate of 5-9mmol/kg/s, and the aerobic system produces ATP at a rate of 1.3mmol/kg/s. After a 6s sprint, PCr is depleted 30-55% which means glycolysis heavily contributes the ATP production. Together PCr and glycolysis have an ATP turnover rate of 11-14mmol/kg/s. Glycogen muscle stores are roughly 300mmol/kg and is most likely not the limiting factor during RSA. In fact, it is the lactate accumulation and metabolic environment that causes a reduction in ATP.

The key role during the rest periods is to return the body to homeostasis. Therefore, if sprints are to continue then rest period needs to be long enough for the aerobic system to resynthesize PCr, remove the accumulated intracellular Pi, and oxidize lactate. Alternatively, $\dot{V}O_{2\max}$ may or may not relate to RSA efficiency. $\dot{V}O_{2\max}$ has been related to work-to-rest ratios greater than or equal to 1:5 where recovery is long enough to replenish PCr and ATP, despite the individual's fitness level. On the other hand, lactate threshold may better relate to RSA is since there is an accumulation of lactate and H^+ ions. Hence, training to improve RSA should target the development of onset of blood lactate accumulation (OBLA). As a matter of fact, the strongest predictor of RSA is anaerobic power during six 30m sprints with 20s rest. In other studies, active recovery during eight intervals of cycling (6s of work and 30s of rest) attenuated the drop in performance by speeding up the removal of lactate and utilizing it for fuel. However, the problem is that sprints in sport do not occur over a constant workload. In addition,

there are two methods of reporting RSA results. One method reports total sprint time which has good reliability ($CV < 3\%$) or the rate of fatigue ($CV < 11-50\%$) which is less reliable and can be reported as the percent sprint decrement (%DS) or the fatigue index (FI). For that reason, total or mean sprint time should be used when reporting RSA results.

Girard, Villanueva, Bishop, 2011

Repeated-sprint ability - Part I, Factors contributing to fatigue

The purpose of this review was to define intermittent exercise and explain the mechanisms and limiting factors associated with short duration sprints. Intermittent sprint activity is characterized by ≤ 10 s sprints with recovery periods long enough to almost completely replenish energy stores (60-300s) and maintain performance. Alternatively, repeated sprint exercise (RSE) imposes ≤ 10 s sprints, but with brief recovery periods (≤ 60 s) that induce significant performance decrements. Practically, time motion analysis done on team sports has shown that sprinting comprises 1-10% of the total distance covered and 1-3% of the total effective playing time. Fatigue is often seen rapidly after the first sprint in RSE and is affected globally from inadequate motor command in the motor cortex (neural factors) to metabolite accumulation intramuscularly (muscular factors). Fatigue development in team sports has been linked to the ability of reproducing sprints over the course of a game. Interestingly, only a 0.8% decrease in sprint speed can significantly alter the likeliness of a player losing possession of the ball while sprinting against an opponent. In order to quantify the decrements in maximal power output over repeated sprints, two methods can be analyzed. First, the fatigue index (FI) characterized by the drop off in performance from the best to the worst sprint, $FI = 100 \times [S_{Best} - S_{Worst}] / S_{Best}$, where S is the power output or speed. Second, the percent decrement score (S_{Dec}), which compares the actual performance to hypothetical “ideal performance” where the best

effort would be replicated in each sprint. The potential benefit of the S_{Dec} is that it takes into account each sprint whereas the former could be influenced by one really good or poor first or last sprint. In addition, S_{Dec} has been shown in previous literature to be the most valid and reliable method. Research has shown that more aerobically inclined individuals have proven to be more fatigue resistant during repeated cycling sprints, which implies that decrements in force production over RSE, and not absolute force generated per se, may be supported by metabolic pathways.

Now sprint performance will depend on the specific mode of exercise, mechanical resistance load, running surface, distribution of the work-to-rest ratio and the number of reps performed, and whether the recovery is active or passive. Other factors that could contribute to decrements in RSE are sex, age, gender, player position, level of competitiveness, and even time of day. Afternoon sessions were shown to produce higher power on the first sprint and therefore a sharper decline in sprint activity, but with an insignificant difference for total work.

On the other hand, muscular factors play a substantial role in fatigue. Specifically, ionic disturbances such as sodium-potassium pump and ATPase activity lead to an accrue of extracellular potassium concentration. This, in turn, impairs membrane excitability and decreases force development most likely by slower inactivation of sodium channels. This will then manifest indirectly by a reduction in action potential amplitude and a slowing of impulse contraction.

Metabolically, RSE requires a high rate of ATP utilization and resynthesis. In fact, after 6s, PCr can deplete 35-55% of its resting levels with a greater reduction seen in fast twitch muscles. Therefore, a more efficient rate of PCr resynthesis during recovery could more

effectively maintain power output over RSE. Additionally, glycolysis accounts for about 40% of the total energy for a single 6s sprint, but becomes progressively inhibited as changes in metabolism shift as sprints continue. Lastly, oxidative metabolism accounts for only 10% of the total energy provision, but may increase up to 40% during the final sprint repetition. This suggests that greater $\dot{V}O_{2\max}$ may allow for greater contribution towards the end of RSE and minimize fatigue.

One last important role in fatigue is the metabolite accumulation. Specifically, H^+ accumulation may affect the contractile machinery and the negative effects on phosphofructokinase (PFK) and glycogen phosphorylase, through the inhibition of ATP from glycolysis, affecting sprint performance. Furthermore, high Pi levels may affect calcium release from the sarcoplasm reticulum (SR). In fact, there has been a negative correlation between S_{Dec} , buffer capacity, and change in blood pH as well as transporters that remove H^+ (MCT1).

McGawley, Bishop, 2014

Oxygen uptake during repeated-sprint exercise

The aim of this study was to measure and estimate the aerobic contribution from the first and last sprints during two 5x6s maximal sprint bouts. Eight female soccer players from the Australian women's national soccer league performed seven experimental sessions, the first being a GXT to measure lactate threshold (LT) and $\dot{V}O_{2\max}$ while the next five sessions included two 5x6s sprints with 24s of active rest at 75%LT. The recovery time between bouts started at 5min for the first day and then increased or decreased based on individual performance. The goal during these sprinting bouts was to determine the minimal amount of rest needed without a drop in total work. The final session included two bouts of 5x6s sprints, but measured the expired air during

the first and last sprint of each bout. The estimated aerobic contribution decreased from the first to the last sprint in each bout. The $\dot{V}O_2$ and aerobic contribution were greater during the final sprint compared to the initial sprint in both bouts. In addition, the $\dot{V}O_2$ attained from the last sprint in each bout was not significantly different from $\dot{V}O_{2max}$ ($p = 0.284$ and $p = 0.448$, respectively). The estimated aerobic contribution and the $\dot{V}O_2$ attained during each bout were correlated with $\dot{V}O_{2max}$. This may suggest that aerobic contribution is limited by $\dot{V}O_{2max}$.

Intermittent Critical Power and Velocity

Dupont, Blondel, Lensel, Berthoin, 2002

Critical velocity and time spent at a high level of $\dot{V}O_2$ for short intermittent runs at supramaximal velocities

The purpose of this study was to determine the intermittent critical velocity (ICV), time spent at $\dot{V}O_{2max}$, and the time spent between 90% and 100% of $\dot{V}O_{2max}$ for short intermittent runs of 15s runs at supramaximal velocities and 15s of passive recovery. Nine physical education students underwent a GXT to determine maximal aerobic speed (MAS) and then performed four randomized intermittent field tests (15s of work and 15s of rest) at 110%, 120%, 130%, and 140% of MAS and one continuous exercise test at 100% MAS. Each field test was conducted on a 200m indoor track, separated by at least two days, and performed until voluntary exhaustion or until the participant could no longer maintain the required velocity. The distance calculated was the number of 15s runs multiplied by the theoretical distance covered at each relative MAS. ICV was determined as the slope of time x distance relationship for each individual. Physiological values such as $\dot{V}O_2$, $\dot{V}CO_2$, and HR were averaged over every five seconds during intermittent runs while blood lactate was taken 2min after each test. The time

spent at $\dot{V}O_{2\max}$ was highest at 120% MAS, however the time spent between 90-100% $\dot{V}O_{2\max}$ was highest in 110% MAS with a significantly increased at 120% MAS as well. ICV was proven not to be significantly different from MAS. $\dot{V}O_{2\max}$ was not reached at 130% or 140% MAS possibly because the duration was too short making the demand for PCr resynthesis and myoglobin reloading during the recovery periods too great. Since 110% and 120% MAS allowed subjects to run at $\dot{V}O_{2\max}$ for longer, intermittent training programs with supramaximal intensities can sustain $\dot{V}O_{2\max}$ for a longer duration and should increase $\dot{V}O_{2\max}$.

Morton, Billat, 2004

The critical power model for intermittent exercise

Traditionally the CP concept has been determined via continuous exercise, but more recently has been adapted to intermittent exercise. As CP is a two component model of aerobic and anaerobic energy systems, with anaerobic being finite in nature, certain restrictions must be applied to intermittent activity to ensure proper estimates of CP and W' . In order to bring about exhaustion the power output during the work bout must be greater than CP and the rest bout must be less than CP, however if power output during the work and rest bouts are less than CP exercise could theoretically continue forever. Since working above CP depletes W' , the rest time will allow partial refilling, but at a slower rate than its depletion. This process will continue until W' is fully depleted and it will be considered the total endurance time.

The purpose of this study was to present the CP model adapted for intermittent exercise and examine whether anaerobic distance capacity (D') and CV differ within the same subjects depending on whether estimates come from continuous or intermittent running. Six endurance trained males athletes (51 ± 6 yr) volunteered and were assessed fit to participate determined

through a cardiological assessment on a cycle ergometer. Each of their CV for continuous running was established from their best performances in 3km, 5km, and 10km races during the season by using the equation, $D_{lim} = W' + CV(t_{lim})$. Subjects randomly performed three intermittent running tests on a 400m oval track separated by at least 48hrs. The first run was performed with 60s of fast running at 120%CV with 60s of slow running at 50%CV, the second run consisted of 180s of fast running at 110%CV and 180s of slow running at 60%CV, and the third run was performed on 30s of fast running at 135%CV and 60s of slow running at 65%CV. Now based on their CV each subject had a set distance to cover in the work and rest bouts and when they could no longer maintain that covered distance the test ended and endurance time was measured.

In all six subjects good fits were observed (0.954 – 0.999) providing realistic values for W' and CV. The W' estimated from continuous running may be less when estimated from intermittent running, but not significantly. Oppositely, CV estimates from continuous running were significantly higher than intermittent running ($p < 0.001$). This shows that predicting intermittent W' from continuous may violate restrictions and that CV and W' could be significantly different when comparing continuous and intermittent running. This study showed successfully completion of the CP model adapted to intermittent activity can yield sensible results given the appropriate placement of data.

Pereira, Freitas, Rodacki, Ugrinowitsch, Fowler, Kokubun, 2009

Evaluation of an innovative critical power model in intermittent vertical jump

The purpose of this study was to implement the CP model to determine critical rest between vertical jumps. Ten physically active males (21.4 ± 2.4 yr) trained in volleyball and

basketball performed 40 counter movement jumps on a force plate with 4s rest, for the first 20 jumps, and 8s rest for the last 20 jumps on the first session. The next three sessions were designed at different rest periods in order to manipulate the number of jumps, total external work, and time to exhaustion that varied between one and 10min. Participants were instructed to jump as high as they can and termination resulted when three consecutive jumps fell under 95% of their maximal jump height. CRI was determined through the linear relationship between three trial's total work done and TTE (rest and work periods) with the slope of this relationship yielding CP and the y-intercept providing W'. The final session was conducted at each individual's CRI where subjects were able to complete more vertical jumps compared to either of the shorter rest periods. Likewise, the longer the rest period the more work done and the longer TTE was observed. This was the first study to manipulate work-to-rest ratios to determine CRI; however the study did not validate CRI by using trials above and below CRI.

Okuno, Perandini, Bishop, Simoes, Pereira, Berthoin, Kokubun, 2011

Physiological and perceived exertion responses at intermittent critical power and intermittent maximal lactate steady state

The aim of this study was to compare physiological and perceptual responses during intensity at ICP and intermittent maximal lactate steady state (MLSS_i). Power output was derived from both continuous and intermittent trials while physiological markers were measured ($\dot{V}O_2$, lactate, HR, and RPE). Ten male college students (24.4 ± 3.7 yr) volunteered for the five phases of the study. The first phase included two familiarization trials and the second determined $\dot{V}O_{2max}$ and maximal aerobic power (MAP). The third phase required four random continuous trials at different workloads to determine continuous CP (CP_C). Similarly, the fourth phase included four random trials with a constant 1:1 work-to-rest ratio (30s work and 30s rest)

to determine ICP. Specifically, ICP was calculated using the 2-parameter hyperbolic power-time equation [$t = W'/(P-CP)$]. The fifth phase involved two or three tests to determine MLSS_i utilizing the same intermittent protocol. This final stage started with ICP intensity, with a duration limit of 30min, and if steady state was achieved the power output increased 10% the following test, but if steady state was not achieved then the power output decreased 10%. During these tests $\dot{V}O_2$, lactate (via earlobe), HR, and RPE were recorded every 5min. ICP correlated with MLSS_i ($r = 0.88$; $p < 0.001$), CP_C ($r = 0.79$; $p < 0.05$), MAP ($r = 0.75$; $p < 0.05$), and $\dot{V}O_{2max}$ ($r = 0.76$; $p < 0.05$). Likewise estimated continuous W' and intermittent W' were similar and correlated ($r = 0.62$; $p < 0.05$). $\dot{V}O_2$ stabilized from the 5th to the 30th min during ICP and MLSS_i. Significant differences were seen for RPE between ICP and MLSS_i after the 20th min which may be due to a slightly higher power output during ICP compared to MLSS_i. HR and lactate produced similar patterns between MLSS_i and ICP. ICP appears to be an aerobic fitness index as it related to aerobic performance parameters (MAP and $\dot{V}O_{2max}$). Also, ICP may be the upper limit of blood lactate and possibly $\dot{V}O_2$ steady state. Overall, ICP witnessed physiological steady state similar to MLSS_i as shown by the strong positive correlation and physiological markers.

Fukuda, Smith, Kendall, Cramer, Stout, 2011

The determination of critical rest interval from intermittent critical velocity test in club-level collegiate hockey and rugby players

The purpose of this study was to examine the relationship between intensity and TTE as a mode of estimating rest periods during interval running. This study utilized the variables from ICV testing to determine CRI and to determine the relationship between the ICV test, CRI, $\dot{V}O_{2max}$, and body composition (air displacement plethysmography) factors related to male

athletes. This project used 14 male hockey and rugby club-level athletes and put them through three different 1:1 ICV work-to-rest ratio protocols at a constant 15s sprint with 15s passive recovery until exhaustion at different intensities relative to their peak velocity. ICV and D' was determined using the linear total distance (L-TD) model and linear regression via the slope of the regression line and the y-intercept respectively. Following the ICV test, CRI was calculated by the TD, the total number of intervals completed, and the ICV [$CRI = (TD/\sum INT)/ICV_{CRI}$]. The ICV provided a testing method using repeated sprints versus a GXT. For each increasing intensity TW, TD, and the number of completed intervals decreased. Moreover, D' ($r = 0.804$; $p = 0.001$) and velocity at VT ($r = -0.0630$; $p = 0.016$) correlated with CRI as well as body fat percent ($r = -0.649$; $p = 0.006$), lean body mass ($r = -0.556$; $p = 0.012$), fat mass ($r = -0.669$; $p = 0.015$), body weight ($r = -0.669$; $p = 0.006$), and relative to $\dot{V}O_{2max}$ ($r = 0.562$; $p = 0.036$). In fact, ICV was shown to be 102% of peak velocity from the GXT. Lastly, body composition was found to potentially impact ICV by increasing energy expenditure during running.

Chidnok, Dimenna, Bailey, Vanhatalo, Morton, Wilkerson, Jones, 2012

Exercise tolerance in intermittent cycling: Application of the critical power concept

The purpose of this study was to apply the CP model to better understand the physiological responses to intermittent exercise. Seven males (26 ± 5 yr) established their CP and W' from a 3min all out sprint on a cycle ergometer and then performed five randomly ordered cycling tests to exhaustion. Subjects completed 60s work bouts at a severe intensity and 30s rest at a low severe intensity, heavy intensity, moderate intensity, or low intensity. The estimations of CP and W' via the work-time model ($R^2 = .99-1.00$), the 1/time model ($R^2 = .99-1.00$), and the intermittent model ($R^2 = .95-1.00$) showed goodness of fit. The duration of exercise increased as the less severe protocols were applied. Similarly, the work done above CP was significantly

greater as the protocol became less intense. When constant work rate performed above CP intramuscular PCr and pH decrease while Pi increases until volitional fatigue. On the other hand, when constant work rate is performed less than CP, pH, Pi, and PCr remain stable. Intermittent exercise allows for some of these fatigue related metabolites to be cleared and PCr to be resynthesized. This, in turn, will delay fatigue and limit the intramuscular environment to a certain degree before fatigue terminates exercise. The recovery period allows for restoration of W' as long as the duration and the intensity of the interval fall below CP. Finally, this can predict exercise tolerance and help prescribe optimal interval training work to rest ratios.

Soares-Caldeira, Okuno, Sales, Grubert, Simoes, Nakamura, 2012

Similarity in physiological and perceived exertion responses to exercise at continuous and intermittent critical power

The aim of this study was to compare the similarities between physiological responses, perceived exertion, and TTE at ICP and continuous CP (CP_C) workloads. The researchers took ten moderately active males (25.5 ± 4.2 yr) through a maximal GXT, four randomized predictive CP_C trials, four randomized predictive ICP trials, one test at CP_C until exhaustion, and one test at ICP until exhaustion on a cycle ergometer with LODE software. Each test was conducted on separate days over five weeks. During the GXT researchers measured blood lactate, HR, $\dot{V}O_2$, and maximal aerobic power (MAP). Subsequently, researchers measured RPE in addition to HR, lactate, and $\dot{V}O_2$ during the ICP and CP_C trials. In fact, this was the first study to examine the physiological and perceptual responses and TTE at ICP and compare it with CP_C. The intermittent protocol utilized a 1:1 of 30s of work followed by 30s of active recovery at 50%MAP. They found that the power-time (P-t) relationship fit well for the predictive ICP and CP_C trials. No physiological differences were found between ICP and CP_C at exhaustion.

Although TTE did not differ between ICP and CP_C in the predictive trials, they differed in the exhaustive trials. There were strong correlations between $\dot{V}O_2\text{max}$ and ICP ($r = 0.90, p < 0.05$), MAP and ICP ($r = 0.95, p < 0.01$), and MAP and CP_C ($r = 0.98, p < 0.01$). Meanwhile, correlations were found between $\dot{V}O_2\text{max}$ and power output with CP_C ($r = 0.91, p < 0.01$), however no correlations were found between TTE and ICP ($r = -0.52, p > 0.05$) or CP_C ($r = -0.50, p > 0.05$). Similarly, there was a significant difference in W' at ICP versus CP_C as well as a poor correlation ($r = 0.44, P = 0.20$) amongst them. The CP model was adequately represented with a high goodness of fit, hyperbolic relationship, determined via power output and TTE. This can then be used to set an intensity that can be sustained without eliciting maximal physiological responses and also set a range of power intensities above ICP with predictable TTE in order to enhance $\dot{V}O_2\text{max}$.

Fukuda, Smith, Kendall, Hetrick, Hames, Cramer, Stout, 2012

The reliability of the intermittent critical velocity test and assessment of critical rest interval in men and woman

The purpose of this study was to determine the reliability of ICV testing and to examine CRI during repeated sprint exercise. Twenty-four college aged males and females ($21.7 \pm 2.63\text{yr}$) participated in four days of testing. After establishing peak velocity (PV) during $\dot{V}O_2\text{max}$ testing on the first day, participants underwent two days of ICV testing at 130%, 110%, and 120%PV with a 1:1 (10s:10s) running protocol on a treadmill. While subjects rested 15min between each run, the relationship between TTE (work bouts), TD, and velocity were analyzed. The ICV and W' were determined through the L-TD model and linear regression where $TD = W' + ICV(t)$. In addition, the CRI was calculated as the amount of TD per interval by ICV, however ICV in this equation accounted for both work and rest periods in TTE. On the final day, CRI

was instituted to perform 120 10s intervals equating to 20min of work. Additionally, HR and RPE were assessed intermittently throughout the test, but only 13 individuals were able to complete all 120 sprints. The results provided reliable measures for ICV and CRI testing as ICCs were 0.89, SEM \pm 0.2m/s (ICV), 0.80, SEM \pm 28.6m (W'), and 0.59, SEM \pm 1.5s (CRI) for the overall group. An increase between trials for W' indicated a significant effect and a greater W' for males compared to females. The average velocity during the CRI trial was significantly greater than the PV from $\dot{V}O_2$ max testing and the first ICV trial. Furthermore, the CRI estimate produced a steady state HR of 96% which is below HRmax. There was a correlation between $\dot{V}O_2$ max and ICV (0.655, $p < 0.01$) and CRI (-0.415, $p = 0.04$). However, this study did not conduct a full validation of CRI with test sessions above and below CRI.

Chidnok, DiMenna, Fulford, Bailey, Skiba, Vanhatalo, Jones, 2013

Muscle metabolic responses during high-intensity intermittent exercise measured by P-MRS: relationship to the critical power concept

The purpose behind this study was to investigate the responses of intramuscular phosphate-linked variables (Pi, PCr, pH, and ADP) in high intensity intermittent exercise with variable recovery periods. Initially, nine recreationally active males (22 ± 3 yr) performed four single leg extension trials, at a constant power output, to determine the hyperbolic power-time curve. These trials developed the means to calculate CP and W' via the nonlinear power-time model, the linear work-time model, and the linear power-inverse of time model. The models were analyzed for goodness of fit and standard error of estimate (SEE) and the best model was chosen for further analysis. Subjects were encouraged to continue exercise until they could no longer maintain the required rate of 40 contractions per min. Afterwards, subjects performed three 60s work bouts with 18s, 30s, or 48s of passive recovery until exhaustion in randomized

order while measuring muscle metabolites (ADP, Pi, PCr, and pH) via phosphorous magnetic resonance spectroscopy (P-MRS) every 1.5s. The constant power outputs were determined via CP and W' and predicted exhaustion after 4, 6, and 8 completed interval cycles. There was no statistical difference between each model's estimation of CP and W', however the linear power-inverse of time model produced the lowest SEE values. Meanwhile, TTE was significantly different between rest times since a longer rest allowed for greater exercise duration. The total exercise time above CP was not statistically significant between the three rest periods. PCr restoration became progressively greater as the recovery interval increased, although the amplitude was twice as high with 48s rest as compared with 18s, and PCr at exhaustion was about 40% of the pre-test values. There were no significant differences in metabolites at the point of exhaustion between the protocols. The work done above CP became greater as the recovery interval increased and it significantly correlated with the amplitude of muscle PCr restoration between work intervals. $\dot{V}O_2$ was linked to PCr as the rate of PCr resynthesis may blunt the rate at which $\dot{V}O_2$ increases to its maximum. Not one metabolite was found to be the cause for fatigue, but rather an all-encompassing change in the muscle tissue milieu. Longer rest durations allowed intramuscular homeostasis to be restored, but the degree to it was dependent upon the duration of the rest period.

Skiba, Clarke, Vanhatalo, Jones, 2014

Validation of a novel intermittent W' model for cycling using field data

The purpose of this study was to validate the W'_{Bal} model, which represents the dynamic state of the remaining W' at any moment, to predict exhaustion (where $W'_{Bal} = 0$). Power meters were retrospectively analyzed from six male and two female well trained triathletes. Files from successfully completed assigned tasks which resulted in exhaustive and non-exhaustive states

were analyzed. Each subject's W'_{Bal} was calculated at the time of exhaustion. There was a significant difference between the W'_{Bal} in exhausted and non-exhausted states ($p < 0.0001$). W'_{Bal} for constant work rate exercise was directly proportional to the difference in $\dot{V}O_2$ between the end of intermittent exercise and $\dot{V}O_{2max}$. Area under the curve analysis (ROC = 0.914, SE: 0.05, $p < 0.0001$) demonstrated that W'_{Bal} model may be at least as accurate as the CP model to calculate W' .

CHAPTER III: DESIGN AND METHODOLOGY

Participants

Twelve healthy recreationally trained males between the ages of 18 and 35 were recruited for this study. It was required that these individuals exercise 2 days per week minimally. Before enrolling in the study, all participants completed a Confidential Medical and Activity Questionnaire as well as a Physical Activity Readiness Questionnaire (PAR-Q) to determine if they had any physical limitations or chronic illnesses that would keep them from performing exercise. Potential participants were excluded from the study if they failed to test at a $\dot{V}O_{2\max}$ of 35ml/kg/min or below. Throughout the study, participants were not allowed to deviate from their normal caffeine consumption, normal timing of food consumption, or other routinely consumed nutritional and dietary intakes within each scheduled testing day. Participants were also told to refrain from vigorous exercise (> 6METS) within 48hrs prior to each testing day. All participants provided informed consent before beginning the study.

Research Design

A within-subject, repeated measures design study was used to determine and validate the critical rest interval during repeated sprint ability testing. Each participant visited the Human Performance Laboratory for an initial screening visit, a maximal graded exercise test (GXT), three testing sessions, and two validation sessions. On the initial visit, anthropometrics were collected and body composition was analyzed and participants were familiarized with the testing protocol. On the second visit, each participant performed a graded exercise test to determine peak oxygen consumption ($\dot{V}O_{2\text{peak}}$), time to exhaustion, and ventilatory threshold (V_T). After completing pre-screening and pre-testing, participants completed three different interval testing

sessions from which critical rest interval will be calculated. Participants completed the entire study over 5 weeks. During these 5 weeks, the participants did not engage in any physical exhausting activity (>6 METS) 24 hours prior to testing.

Variables

The independent variables included in this study were each repeated sprint ability (RSA) testing session with varying rest intervals and the validation sessions. The dependent variables included in this study were: (a) $\dot{V}O_2$ peak, (b) peak power output (PPO), (c) whole body and segmental body composition, (d) total time to exhaustion (TTE), total distance (D), total work (W), and $\dot{V}O_2$ for each RSA test (e), critical rest interval (CRI), intermittent critical power (ICP), and anaerobic working capacity (W') for each RSA test, (f) Time-to-exhaustion, $\dot{V}O_2$, heart rate (HR), and lactate for each validation session above and below ICP.

Instrumentation

- An electronically-braked cycle ergometer (Excalibur Sport, Lode, Groningen, The Netherlands) will be utilized to perform all graded exercise tests.
- Open circuit spirometry (True One Metabolic Cart, Parvo Medics, Inc., Sandy UT) was used in the determination of all metabolic measures.
- Cycle ergometer software (Lode Ergometry Manager V9.1, Lode, Groningen, The Netherlands)
- Bioelectrical impedance analyzer (DF50, ImpediMed, Inc, Pinkenba, QLD Australia)
- Lactate analyzer (Lactate Plus, Nova Biomedical, Waltham, MA)
- Heart rate monitor (Polar FS1, Polar Electro, Inc., Lake Success, NY)

Initial Screening and Testing Methods

Initial Visit (Screening Day):

Prior to participation in the study, each prospective participant visited the Institute of Exercise Physiology and Wellness Human Performance Laboratory and signed an Informed Consent Form and completed a PAR-Q and Confidential Medical and Activity questionnaire. Participants were asked to report to the laboratory in a euhydrated state and fasted for a period of four hours. The participant's body measurements (height, weight) were measured and they underwent body composition testing via bioelectrical impedance analysis.

Body Composition

Bioelectrical Impedance Analysis (BIA)

Subjects were asked to remove their footwear, including socks, and lie supine on a padded table for at least 3min to restore fluid equilibrium. Resting electrodes were placed on the hands, upper thigh, and feet. Two electrodes were placed at the wrist, one bisecting the ulnar head and the other 5cm distal of the ulnar head. One electrode was placed 5cm below the greater trochanter on the anterior side and two electrodes were placed at the ankle. One was positioned in between the malleoli and the other 5cm distal from that point. The skin surface of each electrode placement was shaved and cleaned with an alcohol wipe to maximize electrode contact and signal conductance. Using the BIA device (DF50, ImpediMed, Inc, Pinkenba, QLD Australia), a minute electrical current was conducted through the body to determine body composition. These machines are widely-used commercial devices that are FDA approved. Whole body and leg muscle, and fat mass were estimated while total body water, intracellular water, extracellular water, resistance, and reactance values were recorded for further analysis.

Graded Exercise Test (GXT) and Familiarization

Participants who met the study criteria returned to the Institute of Exercise Physiology and Wellness Human Performance Laboratory and were familiarized with the experimental procedures. During visit 2, participants had their body weight measured on a calibrated physician's scale. In addition, they performed a maximal graded exercise test (GXT) on a cycle ergometer to determine $\dot{V}O_{2\text{peak}}$ and peak power output. Finally, the participants performed a familiarization sprinting session on the cycle ergometer.

Graded Exercise Test (GXT)

Participants performed a continuous graded exercise test on an electronically-braked cycle ergometer (Excalibur Sport, Lode; Groenigen, The Netherlands) to determine maximal oxygen consumption ($\dot{V}O_{2\text{max}}$) and the peak power output (PPO) in watts (W) at $\dot{V}O_{2\text{max}}$ ($\dot{V}O_{2\text{PPO}}$). Prior to testing, each participant was fitted with a Polar Heart Watch system to record their heart rate (Polar FS1, Polar Electro, Inc., Lake Success, NY). Participants began pedaling at a cadence of 60-80 revolutions per minute (RPM) at a workload of 20 W. The workload increased one W every three seconds (a total of 20 W every minute) until the participant was unable to maintain 60-80 RPM or until volitional fatigue. The metabolic cart software calculated $\dot{V}O_2$ and determined the $\dot{V}O_{2\text{max}}$ value during the GXT. The following were general indications for stopping an exercise test in low-risk adults according to ACSM Guidelines: onset of angina or angina-like symptoms; shortness of breath, wheezing, leg cramps, or claudication; signs of poor perfusion: light-headedness, confusion, ataxia, pallor, cyanosis, nausea, or cold and clammy skin; failure of heart rate to increase with increased exercise intensity; participant requests to stop; physical or verbal manifestations of severe fatigue; failure of the testing equipment.

Repeated Sprint Familiarization

The participants performed approximately 10 6-second submaximal and maximal sprints against a load equivalent to $0.75 \text{ N}\cdot\text{kg}^{-1}$ of body mass interspersed by 24 seconds of unloaded cycling.

Gas Exchange Analysis

All gas exchange data was collected using Open circuit spirometry (True One Metabolic Cart, Parvo Medics, Inc., Sandy UT). Twenty minutes prior to each graded exercise test the unit was calibrated with room air and gases of known concentration. Flowmeter calibration was also performed prior to exercise to determine accuracy of flow volume while collecting data.

Participants wore a head unit and mouth piece that stabilized a one-way valve around their mouth. Oxygen and carbon dioxide was analyzed through a sampling line after the gases pass through a heated pneumotach and mixing chamber. Respiratory gases—oxygen (O_2), carbon dioxide (CO_2), ventilation (\dot{V}_E), and respiratory exchange ratio (RER)—were monitored continuously and expressed as 30-second averages (Day et al., 2003). $\dot{V}\text{O}_{2\text{peak}}$ was determined to be the highest $\dot{V}\text{O}_2$ value during the test that coincided with at least two of the following three criteria: (a) 90% of age-predicted maximum heart rate; (b) respiratory exchange ratio > 1.1 ; and/or (c) a plateau of oxygen uptake (less than 150 ml/min increase in $\dot{V}\text{O}_2$ during the last 60 s of the test).

Repeated Sprint Ability Testing

The participant's performed a 4-minute warm-up at a self-selected intensity interspersed with 4 submaximal sprints lasting 4 to 6 seconds on a cycle ergometer. At the conclusion of the warm-up, the participants performed three 6-second maximal sprints against a load equivalent to $0.75 \text{ N}\cdot\text{kg}^{-1}$ of body mass interspersed by 24 seconds of unloaded cycling to determine the

maximal power output (average of the peak power from the three sprints). The warm-up was followed by 5 minutes of passive rest. The participants then performed 6-second sprints against a load equivalent to $0.75 \text{ N}\cdot\text{kg}^{-1}$ of body mass interspersed by 24 seconds of unloaded cycling. The participants continued to complete the 6-second sprints until volitional fatigue as determined by two consecutive sprints where power output values were less than 80% of the maximal power output. Prior to each 6-second sprint, the participants were asked to place their leg in a standardized starting position with their preferred thigh at approximately 45° from vertical in the forward direction.

This protocol was repeated during two additional testing sessions (Visit 4 and Visit 5) with a minimum of 48 hours of recovery between each visit. The rest intervals during the repeated sprint protocol were estimated to produce volitional fatigue between 60 seconds and 600 seconds of work time. This estimation was determined by performance on the first repeated sprint test. Gas exchange analysis (as describe above) was conducted throughout the test to determine oxygen uptake ($\dot{V}\text{O}_2$).

The relationship between the work to rest ratio and the time to exhaustion (the total of all 6-s sprinting bouts) for each of the RSA testing sessions was used to calculate critical rest interval. Specifically, critical rest interval was determined through the comparison of total work and time-to-exhaustion. First, TW, TTE, and number of intervals completed were recorded for each subject over three RSA tests. Then, ICP was estimated through the linear relationship between TW and TTE.

$$W = W' + ICP(TTE) \quad (1)$$

The average work per sprint was calculated as the sum total work over the three RSAs divided by the sum total number of intervals.

$$AveW = \frac{\Sigma TW}{\Sigma \# intervals} \quad (2)$$

Finally, to estimate CRI the average work done per sprint was divided by CP.

$$CRI = \frac{AveW}{ICP} \quad (3)$$

For example, subject 5 performed 19, 16, and 12 sprints throughout his RSAs. He also performed 684s, 480s, and 288s of TTE and 75kJ, 61kJ, and 44kJ of total external work respectively. When applying these values to the ICP equation, his ICP is 77.95J/s. Thus, averaging the total sum of their external work and dividing it by ICP his CRI is estimated to be 49.17s.

Validation Trials

Time-to-exhaustion trials were completed on separate days at rest intervals above and below the critical rest interval determined from the results of the repeated sprint ability tests.

Above Critical Rest Interval Time-to-Exhaustion Trial

Participants were asked to complete 6-second maximal sprints against a load equivalent to $0.75 \text{ N} \cdot \text{kg}^{-1}$ of body mass interspersed by rest periods of unloaded cycling equivalent to their calculated critical rest interval plus an additional 10%. The test was terminated after 75 minutes of exercise or at volitional exhaustion, as indicated by two consecutive sprints where power output values are less than 80% of the maximal power output, if it occurs before 75 minutes. Gas exchange analysis (as describe above) was conducted throughout the test to determine

oxygen uptake ($\dot{V}O_2$). Additionally, heart rate values were recorded following every set of 5 sprints and blood lactate concentrations, taken via finger capillary blood samples and a lactate analyzer (Lactate Plus, Nova Biomedical, Waltham, MA), were determined following every set of 10 sprints. Previous research has shown strong concurrent validity of the Lactate Plus analyzer ($r = 0.97$) compared with the YSI bench top analyzer and the reliability has shown to be very strong ($r = 0.99$, $p < 0.05$) (Hart et al., 2013).

Below Critical Rest Interval Time-to-Exhaustion Trial

Participants were asked to complete 6-second maximal sprints against a load equivalent to $0.75 \text{ N}\cdot\text{kg}^{-1}$ of body mass interspersed by rest periods of unloaded cycling equivalent to their calculated critical rest interval minus an additional 10%. The test was terminated after 75 minutes of exercise or at volitional exhaustion, as indicated by two consecutive sprints where power output values are less than 80% of the maximal power output, if it occurs before 75 minutes. Gas exchange analysis (as describe above) was conducted throughout the test to determine oxygen uptake ($\dot{V}O_2$). Additionally, heart rate values were recorded following every set of 5 sprints and blood lactate concentrations were determined following every set of 10 sprints.

Data Analysis

Breath-by-breath gas exchange analysis data was converted to text files and further analyzed using a custom program within the LabVIEW software (National Instruments, Austin, TX). All $\dot{V}O_2$ and HR data were fit with a cubic spline interpolation function and plotted over time for each trial and analyzed for each high and low value throughout the trial. In order to smooth out the $\dot{V}O_2$ and HR data, a low pass Butterworth digital filter with a cut-off frequency of

0.02Hz was used as recommended by Weir et al. (2004). $\dot{V}O_2$ and HR data were then compared to the highest attained value from each subject's GXT using the same LabVIEW program filter and converted into percentages of $\dot{V}O_{2peak}$ (% $\dot{V}O_{2peak}$) or HRpeak (%HRpeak). Peak power was similarly converted to a percentage of the maximal peak power outputs established prior to each trial (%PPO). The above and below $\dot{V}O_2$, HR, peak power, and mean power were divided into four partitions as follows: 0-25% of TTE (25%TTE), 25-50% of TTE (50%TTE), 50-75% of TTE (75%TTE), and 75-100% of TTE (100%TTE).

Statistical Analyses

All data was analyzed to determine statistically significant changes and differences between trials utilizing SPSS (version 21.0). All data were analyzed for normality via the Kolmogorov-Smirnov and parametric statistics were used for those that were normal and non-parametric statistics were used for non-normal data (RPR). Linear regression was used to estimate ICP and W' . The method proposed by Pereira et al (2009) and previously described was used to estimate CRI. Coefficient of determination (r^2) was used to examine linearity of the work-time relationship. One-way analysis of variance (ANOVA) was used to analyze $\dot{V}O_2$ from the GXT, RSA and validation trials. One-way ANOVA was also used to analyze TTE, TW, $\dot{V}O_2$, and the number of completed intervals for each RSA trial for all subjects. One-way repeated measures ANOVA was used to analyze the eight subjects that performed the same three RSA trials. Paired samples t-tests were performed to compare TTE and mean lactate concentration above or below CRI during the validation trials. A Wilcoxon test was used to analyze RPR during the validation trials. Two-way [time (0-25%, 25-50%, 50-75%, 75-100% of TTE) x trial (above CRI, below CRI)] repeated measures ANOVA was used to examine the changes in $\dot{V}O_2$, HR, Pmax, MP, and TW throughout the validation trials. In the event of

statistical significance, Bonferroni or paired samples t-tests were used for post-hoc analysis.

Pearson product moment correlations were used to analyze CRI and W' with other performance measures during the GXT. Results were considered significant at an alpha level of $p \leq 0.10$.

CHAPTER IV: RESULTS

The descriptive statistics for all participants are listed in Table 1. Twelve participants were recruited and performed three RSA tests, but only eight performed the same RSA tests. Table 2 shows the means and standard deviations (mean \pm SD) for all variables across each RSA trial and Table 3 shows the means and standard deviations for all variables for the eight subjects that completed the RSA trials with the 12s, 18s, and 24s rest periods.

Repeated Sprint Ability Testing

When analyzing the entire sample of subjects during the RSA trials ($n=12$), the maximal power output (P_{max}) determined prior to each RSA and validation trial was not significantly different throughout the study ($F = 1.889$, $p = 0.137$, $\eta^2 = 0.196$) (see Table 2). During the RSA trials, the average work per sprint ($AveW$) ($F = 2.9$, $p = 0.038$, $\eta^2 = 0.272$), average peak oxygen consumption ($Ave\dot{V}O_2$) ($F = 2.466$, $p = 0.066$, $\eta^2 = 0.154$), and TTE ($F = 3.09$, $p = 0.030$, $\eta^2 = 0.285$) were significantly different between the RSA trials with varying rest intervals. However, post-hoc analysis showed no differences between trials for $AveW$ and $Ave\dot{V}O_2$, but TTE was significantly different between the 12s and 36s rest periods ($p = 0.036$).

When analyzing each variable for the group of subjects that performed the same rest periods ($n = 8$), there were significant differences among the number of intervals completed (Intervals; $F = 5.644$, $p = 0.016$, $\eta^2 = 0.446$), TTE ($F = 11.317$, $p = 0.001$, $\eta^2 = 0.618$), TW ($F = 6.178$, $p = 0.012$, $\eta^2 = 0.469$), average work per sprint ($AveW$) ($F = 3.493$, $p = 0.059$, $\eta^2 = 0.333$), peak $\dot{V}O_2$ ($\dot{V}O_{2peak}$; $F = 2.857$, $p = 0.091$, $\eta^2 = 0.290$) and mean $\dot{V}O_2$ ($Ave\dot{V}O_2$; $F = 19.802$, $p = 0.000$, $\eta^2 = .739$) (see Table 3). Post-hoc analysis showed the 12s rest trial was

significantly lower than the 24s rest trial for Intervals ($p = 0.009$), TTE ($p = 0.004$), TW ($p = 0.015$), and Ave $\dot{V}O_2$ ($p = 0.005$), but not for AveW and $\dot{V}O_{2peak}$. Furthermore, the 18s rest trial was significantly greater than the 24s rest trial for Ave $\dot{V}O_2$ ($p = 0.011$).

Critical Rest Interval Estimation

Table 4 displays the CRI, W' , and r^2 values for all 12 subjects. The average CRI was $39.66 \pm 7s$ and W' was $36.58 \pm 16.70kJ$.

Validation Trials

Eleven participants completed both validation trials and four of the participants validation trials were terminated after exercising until the predetermined maximum duration of 75min.

Table 5 shows the comparison of variables above and below CRI. In the above CRI trial TTE was significantly greater than during the below CRI trial ($t = -3.637$, $p = 0.005$), whereas the blood lactate concentration during the below CRI trial was significantly greater than in the above CRI trial ($t = 2.825$, $p = 0.018$). However, there were no differences in mean peak power per sprint ($t = -0.079$, $p = 0.939$), AveW ($t = -0.547$, $p = 0.596$), Intervals ($t = -0.918$, $p = 0.38$), TW ($t = -1.496$, $p = 0.165$), Pmax determined prior to each validation trial ($t = 0.194$, $p = 0.85$), or RPR ($z = -0.222$, $p = 0.824$, $r = -0.067$).

Percentage of Maximal Oxygen Consumption

When analyzing the maximal % $\dot{V}O_2$ values from the work intervals during the CRI validation trials, Mauchly's test indicated that sphericity was assumed for time ($X^2 = 10.206$, $p = 0.075$) and for the trial x time interaction ($X^2 = 4.097$, $p = 0.543$). There was a main effect for time ($F = 5.729$, $p = 0.006$, $\eta^2 = 0.488$) with the 25%TTE and 50%TTE being significantly greater than 100%TTE ($p = 0.011$ and $p = 0.029$, respectively) and for trial ($F = 5.89$, $p = 0.051$,

$\eta^2 = 0.495$) with the below CRI trial ($83.6 \pm 7.6\%$) being significantly greater than the above CRI trial ($78.2 \pm 8.8\%$). There was no trial x time interaction ($F = 1.929$, $p = 0.186$, $\eta^2 = 0.243$) for the maximal $\% \dot{V}O_2$ values from the work intervals during the CRI validation trials (Fig. 1).

When analyzing the minimal $\% \dot{V}O_{2peak}$ values from the rest intervals during the CRI validation trials, Mauchly's test indicated that assumption of sphericity was violated for the trial x time interaction, ($X^2 = 11.458$, $p = 0.047$), however sphericity was assumed for time ($X^2 = 3.955$, $p = 0.563$). Thus, Greenhouse-Geisser estimates of sphericity was used to correct for degrees of freedom for trial x time. There was a main effect for time ($F = 7.745$, $p = 0.002$, $\eta^2 = 0.563$) with significant differences between 50%TTE and 100%TTE ($p = 0.001$) and a main effect for trial ($F = 38.156$, $p = 0.001$, $\eta^2 = 0.864$) with below CRI values ($56.2 \pm 2.9\% \dot{V}O_{2peak}$) being significantly greater than above CRI values ($48.0 \pm 2.1\% \dot{V}O_{2peak}$).

Additionally, there was a trial x time interaction ($F = 6.886$, $p = 0.024$, $\eta^2 = 0.534$) for the minimal $\% \dot{V}O_{2peak}$ values from the rest intervals (Fig. 2). Significant differences were shown between the above and below CRI validation trials for 50%TTE ($p = 0.001$), 75%TTE ($p = 0.002$), and 100%TTE ($p = 0.001$). In the above CRI validation trial, there was a main effect for time for the minimal $\% \dot{V}O_2$ values ($F = 16.453$, $p = 0.000$, $\eta^2 = 0.733$). Mauchly's test indicated sphericity assumed ($X^2 = 6.084$, $p = 0.307$). Follow-up analysis with pairwise comparisons showed that 100%TTE was significantly different than 25%TTE ($p = 0.003$) and 50%TTE ($p = 0.004$) (Fig. 1). In the below CRI validation trial, there was no main effect for time for the minimal $\% \dot{V}O_2$ values ($F = 1.66$, $p = 0.211$, $\eta^2 = 0.217$).

Percentage of Maximal Heart Rate

When analyzing the maximal %HR values from the work intervals during the CRI validation trials, Mauchly's test indicated that assumption of sphericity was violated for time ($X^2 = 14.271$, $p = 0.016$), but not for trial x time ($X^2 = 10.479$, $p = 0.068$). Greenhouse-Geisser estimates of sphericity was used to correct for degrees of freedom for time. There was a main effect for trial ($F = 8.93$, $p = 0.024$, $\eta^2 = 0.598$) with below CRI values ($87.7 \pm 2.3\%$ HRpeak) significantly greater than above CRI values ($82.6 \pm 1.9\%$ HRpeak), and a main effect for time ($F = 12.832$, $p = 0.005$, $\eta^2 = 0.681$) with significant differences between 25% TTE and both 50% TTE ($p = 0.008$) and 75% TTE ($p = 0.038$) and between 75% TTE and 100% TTE ($p = 0.031$).

Additionally, there was a trial x time interaction ($F = 4.51$, $p = 0.016$, $\eta^2 = 0.429$) with significant differences between the above and below CRI validation trials at 50% TTE ($p = 0.036$), 75% TTE ($p = 0.041$), and 100% TTE ($p = 0.022$). In the above CRI validation trial, there was a main effect for time for the maximal %HRpeak values ($F = 4.453$, $p = 0.017$, $\eta^2 = 0.426$). Mauchly's test indicated sphericity assumed ($X^2 = 8.734$, $p = 0.127$). Follow-up analysis with pairwise comparisons did not detect any significant differences between time points (Fig. 2). In the below CRI validation trial, there was a main effect for time for the maximal %HRpeak values CRI ($F = 12.973$, $p = 0.005$, $\eta^2 = 0.684$). Mauchly's test indicated sphericity was assumed ($X^2 = 14.66$, $p = 0.014$). Pairwise comparisons detected significant differences between the 25% TTE and both 50% TTE ($p = 0.010$) and 75% TTE ($p = 0.030$) (Fig. 3).

When analyzing the minimal %HR values from the work intervals during the CRI validation trials, Mauchly's test indicated that assumption of sphericity was violated for time ($X^2 = 12.436$, $p = 0.033$), but not for trial x time ($X^2 = 4.469$, $p = 0.492$). Hence, Greenhouse-Geisser

estimates of sphericity was used to correct for degrees of freedom for time. There was a main effect for trial ($F = 18.774$, $p = 0.005$, $\eta^2 = 0.758$) with the below CRI values ($77.6 \pm 3.8\%HR_{peak}$) being significantly greater than the above CRI values ($68.8 \pm 3.5\%HR_{peak}$), as well as a main effect for time ($F = 15.049$, $p = 0.004$, $\eta^2 = 0.715$) with 25% TTE being significantly different than 50% TTE ($p = 0.004$) and 75% TTE ($p = 0.039$). There was no trial x time interaction ($F = 0.897$, $p = 0.462$, $\eta^2 = 0.130$) (Fig. 4).

Relative Percentage of Peak Power Output (%Pmax)

When analyzing %Pmax throughout the validation trials, Mauchly's test indicated that the assumption of sphericity was met for time ($X^2 = 4.612$, $p = 0.473$) and trial x time ($X^2 = 10.59$, $p = 0.065$). There was a main effect for time ($F = 29.392$, $p = 0.000$, $\eta^2 = 0.830$) with significant differences between 25% TTE and 75% TTE ($p = 0.007$), 25% TTE and 100% TTE ($p = 0.001$), 50% TTE and 100% TTE ($p = 0.006$), and 75% TTE and 100% TTE ($p = 0.003$). There was no main effect for trial ($F = .223$, $p = 0.654$, $\eta^2 = 0.036$) or a trial x time interaction ($F = .357$, $p = 0.784$, $\eta^2 = 0.056$) (Fig. 5).

Mean Power (AveMP)

When analyzing AveMP throughout the validation trials, Mauchly's test indicated that assumption of sphericity was met for time ($X^2 = 4.581$, $p = 0.477$) and trial x time ($X^2 = 5.520$, $p = 0.365$). There was a main effect for time ($F = 39.377$, $p = 0.000$, $\eta^2 = 0.868$) with significant differences between 25% TTE and both 75% TTE ($p = 0.002$) and 100% TTE ($p = 0.002$), between 50% TTE and both 75% TTE ($p = 0.023$) and 100% TTE ($p = 0.001$), and between 75% TTE and 100% TTE ($p = 0.010$). There was no main effect for trial ($F = .510$, $p = 0.502$, $\eta^2 = 0.078$) and no trial x time interaction ($F = .630$, $p = 0.605$, $\eta^2 = 0.095$) (Fig. 6).

Average Total Work (TW)

When analyzing average total work throughout the validation trials, Mauchly's test indicated that assumption of sphericity was met for time ($X^2 = 6.349$, $p = 0.283$) and trial x time ($X^2 = 5.128$, $p = 0.409$). There was a main effect for time ($F = 39.593$, $p = 0.000$, $\eta^2 = 0.868$) with significant differences between 25% TTE and both 75% TTE ($p = 0.002$) and 100% TTE ($p = 0.002$), between 50% TTE and both 75% TTE ($p = 0.001$) and 100% TTE ($p = 0.002$), and between 75% TTE and 100% TTE ($p = 0.042$). There was no main effect for trial ($F = .510$, $p = 0.502$, $\eta^2 = 0.078$) and no trial x time interaction ($F = 0.415$, $p = 0.745$, $\eta^2 = 0.065$) (Fig. 7).

Relationships between Critical Rest Interval, W' , and Graded Exercise Test Variables

Pearson product moment correlations noted a significant relationship between W' and both GXT absolute $\dot{V}O_{2peak}$ (0.84, $p = 0.001$) and GXT maximal power output (0.834, $p = 0.001$). CRI was negatively correlated with VT (-0.516, $p = 0.086$), but no significant relationship was observed between absolute $\dot{V}O_{2peak}$ and CRI (-0.35, $p = 0.265$) or relative $\dot{V}O_{2peak}$ and CRI (-0.371, $p = 0.236$).

CHAPTER V: DISCUSSION

This investigation examined the relationship between multiple work-to-rest ratios and TTE to predict CRI during cycle ergometry. Differences were shown in the number of sprint intervals completed, time-to-exhaustion, total work, and average $\dot{V}O_2$ during RSA testing with varying rest intervals. Conversely, maximal power output values throughout RSA testing procedures did not differ. The use of RSA data was used to develop CRI estimates from the work-time relationship and confirmed through a strong linear relationship between these variables. During the CRI validation trials, significant differences in time-to-exhaustion, blood lactate concentration, average $\dot{V}O_2$, maximal $\dot{V}O_2$ and HR in response to the sprint intervals, and minimal $\dot{V}O_2$ and HR in response to the rest intervals were observed. Furthermore, over the course of the CRI validation trials, the minimal $\dot{V}O_2$ in response to the rest intervals and the maximal HR in response to the sprint intervals were shown to exhibit significantly different response patterns to maximal exercise with rest periods above and below CRI.

Repeated Sprint Ability Testing

In this investigation, each subject completed an initial RSA test with a 24-second rest interval while subsequent RSA protocols were modified according to an individual's performance. A minimal difference in rest interval time of 6 seconds was determined a priori and, as a result, eight of the 12 study participants completed RSA testing with similar rest interval times of 12s, 18s, and 24s, while the maximum rest period was 36s for two participants. For the eight participants who completed RSA tests with similar work-to-rest ratios, the number of intervals completed, time-to-exhaustion, and total work were significantly greater in the 24s rest protocol when compared to the 12s rest protocol. Accordingly, increased rest time should

allow for an enhanced ability to replenish myoglobin stores and PCr resynthesis after a maximal sprint (Glaister, 2005, Billaut & Basset, 2007). Thus, more time to recover equates to a greater repletion of myoglobin and PCr translating into an increased likelihood of performing a greater number of intervals as well as a longer time to fatigue during repeated sprinting. In a similar CRI study, Pereira et al. (2009) showed a significant increase in time to exhaustion and total work during repeated jumps interspersed with longer rest intervals.

In the current investigation, the average $\dot{V}O_2$ was significantly different across all RSA trials with decreased values for each successive increment in rest duration. Likewise, Chidnok et al. (2012) showed increasing $\dot{V}O_2$ values and less time to exhaustion as recovery periods became shorter over four different intermittent bouts of cycling. The number of intervals completed during repeated sprint exercise may depend on the recovery kinetics of $\dot{V}O_2$ as well as the concomitant impact on PCr concentrations and other metabolic by-products (K^+ , P_i , H^+) (Dupont et al, 2010, Jones et al., 2010). Therefore, $\dot{V}O_2$ remains elevated during the rest interval from the preceding work bout and continues to increase incrementally in an attempt to maintain homeostasis during high intensity exercise. Previously, Dupont et al. (2010) found a negative correlation between percent decrement over repeated sprints and $\dot{V}O_{2peak}$ ($r = -0.83$, $p < 0.001$). This implies that anaerobically trained individuals need more time to recover than aerobically trained individuals which is further supported by the positive correlation between CRI and W' ($r^2 = 0.804$, $p = 0.05$) reported by Fukuda et al. (2011) during intermittent treadmill running.

Critical Rest Interval Estimation

While training for intermittent activities, an important element to consider is energy contribution and training at specific work-to-rest ratios in order to mimic the specific energy

system requirements. During the current investigation, maximal RSA tests were used to calculate CRI and, in order to do so, intermittent bouts with work-to-rest ratios ranging from 1:2 to 1:6 were selected. Of these ratios, 1:4 and 1:5 are found most commonly in the literature (Morin et al., 2011, Fitzsimmons et al., 1993, Gaitanos et al., 1993); however, various other ratios within this range have also been utilized (Fukuda et al., 2011, Fukuda et al., 2012, Billaut and Basset, 2007). The current investigation observed an average CRI of 39.7s which places the work-to-rest ratio at ~1:6.5. In comparison, Pereira et al. (2009) observed an average CRI of 7.5s while utilizing repeated counter movement jumps. According to Laffaye et al. (2014), the mean flight time duration of a single counter movement jump for college or professional level male athletes is 500ms, however the researchers suggested that the duration of a full jump from initiation, to lift off, to landing is ~3s. Assuming the counter movement jumps in Pereira et al. (2009) fell within a 2-4s range, then the CRI would fall within a 1:2-1:4 work-to-rest ratio. Alternatively, when CRI was analyzed in treadmill running with sprint intervals of 10s to 15s, the CRI work-to-rest ratios fell between ~1:2.5 and ~1:2 (Fukuda et al., 2012, Fukuda et al., 2011). In applied settings, average work-to-rest ratios of ~1:6 have been reported during competitive rugby (Cunniffe et al., 2009) and taekwondo matches (Matsushigue et al., 2009).

Consequently, rest periods are vital for recovery and prolonged intermittent maximal exercise. In particular, PCr can be depleted up to 40% within 10s, but is 84% restored after 2min (McMahon and Jenkins, 2002, Turner and Smith, 2013). Dawson et al. (1997) reported PCr stores at 70% resting concentrations after 30s recovery from a single 6s maximal cycling sprint and only 45% of resting levels after 24s of recovery between five 6s sprints. In turn PCr levels affect ATP resynthesis (Dawson et al., 1997, Glaister, 2005, McMahon and Jenkins, 2002, Turner and Smith, 2013), as demonstrated by, reduced ATP concentrations of 16% after a single

6s sprint and 34% after five 6s sprints that are replenished by up to ~73% of resting levels after 30s of recovery (Dawson et al., 1997). In addition to PCr and ATP, myoglobin stores are fully replenished after 20s (Glaister, 2005). ATP is stored within muscle at ~20-25mmol/kg dry muscle with peak turnover rates of 15mmol/kg dm/s which is enough to fuel 1-2s of maximal work (Glaister et al., 2005). PCr, which contributes to the ATP pool and is responsible for the majority of the ATP peak turnover rate accounting for 5-9mmol/kg dm/s, is stored in the amount of 80mmol/kg dry muscle, and can be depleted within 10s of maximal work (Glaister et al., 2005, Turner and Stewart, 2013, Gastin, 2001). Since PCr resynthesis is partially restored via aerobic contributions, it is also dependent on the length of the rest period, with a longer rest period restoring greater PCr (Turner and Stewart, 2013). Therefore, it appears that the work-to-rest ratio resulting from CRI estimation is dependent upon the high intensity intermittent protocol being selected and further tests are warranted to compare a variety of exercise modes.

The 12 subjects in the current investigation produced a strong linear relationship between total work and time to exhaustion ($r^2 = 0.952 \pm 0.081$, range = 0.705 – 1.000). Data provided by Pereira et al. (2009) displays similar linearity ($r^2 = 0.995 \pm 0.007$) during intermittent repeated jumps, while Fukuda et al. (2011) utilized the linear total distance model, an analogue of linear total work for running, for repeated treadmill sprints with $r^2 = 0.99-1.00$. Furthermore, Bull et al. (2000) examined a variety of mathematical equations to estimate CP from steady-state cycling bouts, with the linear total work model, showing to be the most precise ($r^2 = 0.997-1.000$), however, the r^2 values ranged from 0.847-1.000 irrespective of the mathematical model applied. Equally, Moritani et al. (1981) reported $r^2 = 0.982 - 0.998$ during steady-state cycle ergometry sessions at varying workloads. Given the linear relationship found in this study, it can be concluded that the relationship between total work and time to exhaustion is appropriate for use

with RSA testing with varying rest intervals and is similar to previous investigations across several exercise modalities.

Pereira et al. (2009) observed much lower W' ($12.9 \pm 5.8\text{kJ}$) than that estimated in the current investigation of $36.58 \pm 16.7\text{kJ}$, however it is important to note that W' from counter movement jumps with a duration of 2-4s should theoretically be different than cycling maximally for 6s due to the movement pattern and the amount of muscle mass recruited. Previous investigations with repeated intermittent cycling work bouts have calculated W' within 22.8-72.3kJ, hence the W' from this investigation lies within that particular range (Chidnok et al., 2012). During intermittent critical power estimation utilizing cycle ergometry with 30s of work and 30s of rest, Okuno et al. (2011) found similar mean W' values (27.3kJ) compared with our results. In contrast to cycle ergometry, Cheng et al. (2012) found lower W' values in rowers (13-16kJ) and Fukuda et al. (2014) found lower W' (8.28kJ) values in ski ergometry. The discrepancy between modes of exercise could be attributed to the amount of muscle mass needed for the specific movement.

Validation Trials

During the CRI validation trials, the lactate concentration, average $\dot{V}O_2$, and average HR values were significantly greater in the below CRI trial compared to the above CRI trial. In comparison to maximal aerobic power, the below and above CRI trials showed significantly lower $\dot{V}O_2$ peaks compared to those determined via GXT ($p = 0.094$ and $p = 0.016$, respectively). Differences in lactate concentration in response to shorter rest periods may be evidence of both increased CO_2 production and O_2 consumption, greater respiration, and a greater accumulation of H^+ ions (Glaister et al., 2005). The fatigability of glycolytic fibers and the

necessity of those fibers to recover between work intervals, emphasizes the importance of aerobic fitness as a greater number of oxidative fibers have been shown to better correlate with the capacity to perform repeated sprint exercise (Thebault et al., 2011).

During the current investigation, blood lactate levels displayed a substantial contribution from the glycolytic energy system similar to previous reports of repeated sprint testing. Glaister et al. (2005) noted comparable blood lactate levels after 10 and 20 sprints with 5s of work and 30s of rest (8-10mmol/L), while Balsom et al. (1994) reported levels of 8.5 ± 0.8 mmol/L after 10 6s sprints with 30s of rest. In CP studies examining the work-time relationship, Okuno et al. (2011) reported comparable blood lactate concentrations between intermittent bouts (6.9 ± 2.6 mmol/L) and maximal lactate steady state bouts (5.7 ± 1.0 mmol/L) as well as a plateau of blood lactate by 30min, while Chidnok et al. (2012) observed end blood lactate levels between 8-10mmol/L during intermittent cycling. Interestingly, Thebault et al. (2011) detected blood lactate in excess of 10mmol/L during a RSA protocol, suggesting the need to counteract acidosis during recovery in repeated sprints via rapid resynthesis of PCr and the removal of Pi in order to delay muscular fatigue. Furthermore, Drust et al. (2000) showed average blood lactate concentrations of 7.7mmol/L in a soccer specific intermittent protocol lasting 46min. Thus, our lactate levels fall within values observed in anaerobic intermittent laboratory-based and field-based exercise bouts of similar duration.

During the CRI validation trials, no significant differences were found for maximal power prior to the testing protocols, total work during the trials, or the number of intervals completed. It is possible that 10% above and below CRI was not large enough to illustrate differences in the number of intervals or total work completed, especially if the CRI estimate was not precise (Hill and Smith, 1999). Previous evidence has suggested that time to exhaustion at

CP has a substantial positive practice effect of 27% (Hill and Smith, 1999) which could explain why the current study did not have a significant change in the number of intervals completed between the two validation trials near CRI. Poole et al. (1988, 1990) also concluded that $\dot{V}O_2\text{max}$ would be elicited by an intensity 8-11% above CP, but the lack of precision in estimating CP could skew the results. Therefore, further revision of the existing definition of the CRI may be warranted.

Furthermore, peak power, mean power, average work, and RPR throughout the testing sessions were not significantly different. However, it should be noted that in each test, participants were instructed to perform maximally until exhaustion as denoted by power outputs lower than 80% of the initial power values. Given the maximal efforts of each participant, peak and mean power should remain similar amongst the two trials. In contrast, Glaister et al. (2005) noticed a significant difference in mean power between two intermittent protocols, however the protocols implemented 5s maximal sprints with either 10s or 30s of rest. These rest periods are substantially different than the longer rest periods in the above and below CRI trials during the current investigation, with the shortest being 28s. Thus, the length of recovery is critical to resynthesize PCr to produce significant power output (Thebault et al., 2011, Dupont et al., 2010, Glaister, 2005). Due to the consistent 6s maximal sprints between above and below CRI, the similar decrements in peak and mean power over the trials, and the comparable number of intervals performed, similar total work and average work per sprint between trials in the data could be expected. Notably, Pereira et al. (2009) reported similar mean work per jump between trials of different rest periods. In support of the lack of statistical significance in RPR between trials in the current investigation, Glaister et al. (2007) reported no significant differences in subjectively perceived fatigue between two multiple sprint cycling protocols one being 5s of

work and 10s of rest and the other being 5s of work and 30s of rest. Consequently, these performance variables did not sufficiently distinguish between the above and below CRI trials.

Maximal $\dot{V}O_2$ in response to the sprint intervals was significantly greater in the below CRI validation trial as compared to the above CRI trial (83.6% vs. 78.2%, respectively). The recovery between sprints affects the body's ability to return to homeostasis, and the differential response during the maximal work bouts in the above and below CRI trials appear to fall within the heavy and severe exercise intensity domains, respectively. The maximal $\dot{V}O_2$ response elicited by the subjects during the repeated sprints in the above CRI trial ranged from 73-81% $\dot{V}O_2$ peak and the below CRI trial ranged from 77-88% $\dot{V}O_2$ peak. CP has been deemed the demarcation between heavy and severe exercise intensity which occurs at $\sim 80\% \dot{V}O_{2max}$ (Poole et al., 1998, Hill and Smith 1999, Jones et al., 2010). Furthermore, Hill and Smith (1999) found that recreationally trained men and women were able to maintain steady state cycling at CP for a duration of 51.3min to 65min which supports the length of time to exhaustion observed in the current study when participants cycled above or near CRI. According to field based soccer data of elite and amateur athletes, $\dot{V}O_2$ levels (70-80%) were consistent with the above CRI trial mean $\dot{V}O_2$ (Makaje et al., 2012, Bangsbo et al., 2007, Balsom et al., 1992). In summary, $\dot{V}O_2$ values near CRI coincide with the demarcation between heavy and severe exercise, with the below CRI trial tending to be within the severe intensity domain and the above CRI trial tending to be in the heavy intensity domain.

Minimal $\dot{V}O_2$ in response to the rest intervals was significantly greater in the below CRI validation trial as compared to the above CRI trial (56.2% vs. 48.0%, respectively). The minimal $\dot{V}O_2$ response elicited by the subjects during the repeated sprints in the above CRI trial ranged from 46-53% of $\dot{V}O_2$ peak and the below CRI trial ranged from a minimum of 53-59% of $\dot{V}O_2$

peak. Glaister et al. (2005) reported a difference (~16%) in mean $\dot{V}O_2$ during recovery with the shorter rest protocol (10s) being greater than the longer rest protocol (30s). The below CRI trial in the current investigation resulted in significantly higher blood lactate than the above CRI trial, demonstrating an increase in metabolic by-products and a decrease in pH likely reducing the response of glycolytic enzymes, the rate of ATP resynthesis, and peak force (Fitts, 2008). This process increases the need for oxidative metabolism to produce ATP and, subsequently, increases the response of $\dot{V}O_2$ above resting values during recovery (Gastin 2001, Alexandre et al., 2012). While simulating team sport performance, Drust et al. (2000) observed elevated oxygen consumption and minute ventilation during the recovery periods in the second half of a soccer specific intermittent protocol showing the importance of aerobic metabolism during prolonged intermittent exercise. The demarcation point between moderate and heavy exercise intensity has been suggested to occur around VT or LT (59-73% $\dot{V}O_{2max}$) in male adults (Fawkner et al., 2002, Mendes et al., 2013, Carter et al., 2002). The currently reported $\dot{V}O_2$ responses lie just underneath VT or LT in the below CRI trial and even less in the above CRI trial. The higher $\dot{V}O_2$ response and lactate during the below CRI trial suggests a greater need for aerobic efforts with PCr and ATP resynthesis (Girard et al., 2011, Glaister, 2005, Glaister et al., 2005, McMahon and Jenkins, 2002). Therefore, CRI may distinguish between the physiological responses associated with both the moderate versus heavy recovery intensities, as well as heavy versus severe work intensities.

When examining the time course of physiological responses to the validation trials, irrespective of the rest interval, maximal and minimal $\dot{V}O_2$ in response to the work and rest intervals, respectively, decreased between 50% and 100% TTE. During high-intensity exercise lasting less than 10s, the ATP-CP is the dominant energy system, accounting for 50% of energy

requirements with concomitant contributions of the glycolytic (35%) and oxidative systems (15%) (Wells et al., 2009). As exercise duration increases, glycolytic substrate becomes depleted, as denoted by the increased blood lactate concentrations during the validation trials, and additional energy requirements are placed upon the other energy systems. Furthermore, the oxidative system is tasked with the removal of metabolic by-products. The subsequent accumulation of lactate and H^+ , as well as the rapid hydrolysis of ATP, decrease blood pH, resulting in reduced shortening velocity and impaired cross-bridge binding (Fitts, 2008, Cooke, 2007, Debold et al., 2008). Furthermore, this effect is observed more so in fast twitch fibers with a greater reduction in intracellular ATP versus slow twitch fibers (Debold et al., 2008). Finally, with repetitive actin-myosin cross-bridge activation, intramuscular ADP can reduce calcium re-uptake and inhibit metabolic enzymes leading to decreased force and muscle relaxation (Williams and Ratel, 2009). While investigating the metabolic response to RSA testing, Glaister (2005) noted that oxygen availability during multiple sprint work, under hypoxic conditions, with 6s sprints interspersed with 30s rest periods was associated with a reduced $\dot{V}O_2$. This may stem from an increased intramuscular accumulation of blood lactate and, possibly, the magnitude of aerobic contribution to ATP resynthesis and the rate of PCr resynthesis during the recovery periods. This multifactorial response with a shift towards greater PCr predominance, slightly less oxidative reliance, fatigue of glycolytic muscle fibers, and a decreased recruitment of specific muscle fibers may have led to the reduction in $\dot{V}O_2$ towards end of the validation trials.

During the below CRI trial no differences in minimal $\dot{V}O_2$ were found throughout the testing procedure, while minimal $\dot{V}O_2$ during the above CRI trial decreased after 50% TTE. Furthermore, minimal $\dot{V}O_2$ was significantly greater in the below CRI trial than the above CRI trial after 50% TTE. The time to exhaustion of the ATP-CP system is reported to be

approximately 12-15s, the time needed to replenish 50% of the required fuel sources is 20-30s, and the time needed for full recovery is 3min (Wells et al. 2009). A general explanation for the differing patterns of $\dot{V}O_2$ response would be the inability to appropriately replenish the ATP-CP system during the below CRI trial and the additional requirement of the oxidative system, as denoted by the maintenance of $\dot{V}O_2$ throughout the duration of the TTE. This explanation is further supported by the relationship between $\dot{V}O_2$ kinetics and RSA performance. Dupont et al. (2010) found a significant positive correlation with the time constant associated with the fast component of $\dot{V}O_2$ off kinetics following severe intensity exercise and percent decrement of power over the course of repeated sprints. In summary, the difference in rest interval duration resulted in changes in energy system contribution as denoted by the different minimal $\dot{V}O_2$ response between the above and below CRI validation trials.

Maximal (above CRI: 82.6%HRpeak; below CRI: 87.7%HRpeak) and minimal (above CRI: 68.8%HRpeak; below CRI: 77.6%HRpeak) HR values during the sprint intervals were significantly different between validation trials with higher HR values during the below CRI showing that participants worked at a greater intensity in response to a shorter rest period. The maximal HR response elicited by the subjects during the repeated sprints in the above CRI trials ranged from 83-87% of HR peak and the below CRI trial ranged from 85-91% of HR peak. The maximal HR values in the below CRI trial may be due to greater HR elevations during the work interval and the maintenance of higher heart rates during shorter recovery periods compared with the above CRI trial (Drust et al., 2000). Previous literature in team-based sports, such as soccer and rugby, illustrate physiological demands, activity profiles, and game analysis equivalent with results of this study (Impellizzeri et al., 2005, Makaje et al., 2012, Alexandre et al., 2012) These HR values correspond with the American College of Sports Medicine criteria for vigorous

exercise (77-95%HRmax) (Swain, 2014). Additionally, the minimal HR response elicited by the subjects during the repeated sprints in the above CRI trial ranged from 67-74% of HR peak and the below CRI trial ranged from a minimum of 74-82% of HR peak. Similar to $\dot{V}O_2$, these HR values distinguish between moderate and vigorous exercise intensity according to the American College of Sports Medicine criteria for moderate (64-76%HRmax) and vigorous exercise (77-95%HRmax) (Swain, 2014). In summary, the minimal and maximal HR response to the repeated sprint intervals with rest periods above and below CRI differentiate between the moderate or vigorous intensity domains, respectively (Swain, 2014).

Additionally, during the below CRI trial maximal HR response was shown to increase through 75%TTE and plateau at 100%TTE, while maximal HR during the above CRI showed no difference throughout the testing session. Furthermore, maximal HR response was significantly greater in the below CRI trial than the above CRI trial after 50%TTE, illustrating continued metabolic strain throughout the below CRI trial. During simulated and match play game analysis of soccer and rugby, there appears to be a drop in average %HRmax during the second half compared to the first half across all levels of competition showing that there may be a drop off in HR response over an extended period of exercise (Impellizzeri et al., 2005, Alexandre et al., 2012, Cunniffe et al., 2009, Krstrup et al., 2006). This may be due to substrate depletion, the rhythm of the game, tactical shifts, or psychological aspects (Alexandre et al., 2012). Playing time in soccer and rugby games extended about the same duration as the CRI trials and appeared to have decreased HR values during the course of the second half in competitive and simulated matches. Therefore, drastic repetitive changes in intensity during repeated sprints over a prolonged duration may affect the oxidative capacity of the active muscles which, in turn, may limit $\dot{V}O_2$ and cause a drop in HR closer to TTE (Alexandre et al., 2012). This response is

evident from the difference between the validation trials with the above CRI trial showing a drop off in HR over time as opposed to the below CRI trials showing stable values.

Mean power peak power, and total work decreased throughout the validation trails with no difference between above CRI and below CRI. A greater decrement in the relative maintenance of power output during the below CRI trial was expected in comparison with the above CRI trial. However, the maintenance of relative peak power decrement over time was similar between trials until the expected cut-off threshold of 80%Pmax. Mean power and total work decreased with a similar pattern between both trials. However, this is to be expected from maximal exercise as participants were instructed to perform each sprint with maximal effort. In comparison, Billaut and Basset, (2007) found no significant differences over 10 sprints in peak power decrement using different recovery patterns. In contrast, Glaister et al. (2005) noted a significant difference in mean power between 10s and 30s of rest with 20 5s sprints, however the rest in the above and below CRI trials may have allowed for a significantly greater recovery of PCr and ATP in order to maintain relative power output for an extended duration. Additionally, the importance of oxygen availability may dictate the magnitude of recovery in-between sprints and may have a profound impact on peak and mean power (Dupont et al., 2010). With regards to total work done, Pereira et al. (2009) reported non-significant decrements in external work over time during repeated counter movement jumps; however, researchers used a 95% maximal jump height cut off criteria to terminate each testing session. Traditionally, CP has been estimated through submaximal testing, but given the nature of maximal effort repeated sprints and practicality to team-based sports, CRI estimates were developed through maximal testing procedures.

The present investigation found that W' is significantly related to $\dot{V}O_{2peak}$ and maximal power output from the GXT. There were no significant relationships between absolute or relative $\dot{V}O_{2peak}$ and CRI, however CRI was negatively correlated with VT. $\dot{V}O_{2max}$ may be dependent on the RSA protocol and may not be related to protocols with work-to-rest ratios greater than 1:5 where recovery is long enough to replenish ATP and PCr despite fitness levels (Turner and Stewart, 2013). Thus, lactate threshold may serve as a better indicator for RSA since there is an accumulation of blood lactate and H^+ (Turner and Stewart, 2013, Dardouri et al., 2014). Jenkins and Quigley, (1991) found no relationship between CP and $\dot{V}O_{2max}$. With regard to high-intensity intermittent exercise, Dardouri et al. (2014) found no significant relationship between $\dot{V}O_{2max}$ and RSA performance parameters and found W' to be the only predictor of RSA performance. However, previous literature has found ICP and ICV to correlate with $\dot{V}O_{2max}$ (0.76, $p < 0.05$ and 0.655, $p < 0.01$, respectively) when utilizing 1:1 work-to rest ratios (Okuno et al., 2011, Fukuda et al., 2012). Moreover, $\dot{V}O_{2max}$ was found to be correlated with CRI (-0.415, $p = 0.04$) (Fukuda et al., 2012). Discrepancies in the literature regarding the relationship between repeated sprint performance and aerobic capacity reveal the need for further investigation.

One of the limitations of the present study was the smaller than anticipated sample size due to the methodological approach selected and the diverse fitness levels of participants. Given the discrepancies between varying fitness levels and the distinctive estimate of CRI, a small subset of the recruited participants performed RSA testing with similar work to rest ratios. While our linear relationship held true for the RSA protocols, 6s in-between each RSA may not have been far enough apart to elicit significant differences in the number of intervals completed and total work done amongst each of the three testing sessions or the validation trials. However,

6s of separation appears to be enough to produce CRI estimates that elicited changes in physiological variables such as blood lactate, $\dot{V}O_2$ peak, and mean $\dot{V}O_2$ and HR.

Conclusions

In conclusion, CRI estimated from RSA testing distinguished between adjacent intensity domains during work and rest intervals in a manner similar to that previously described by CP developed from the work-time relationship. Differences in the minimal $\dot{V}O_2$ response to the rest intervals and the maximal HR response to the work intervals suggest distinct physiological responses during repeated 6s cycling sprints with rest periods above and below CRI. Blood lactate and average $\dot{V}O_2$ were significantly greater in the below CRI trial, but the number of intervals completed and total work did not significantly change between above and below CRI. Therefore, determining CRI from RSA using the work-time relationship may be a viable method. However, the discrepancy between unchanging performance variables versus changing physiological variables provides opportunities for future investigation. Since blood lactate, $\dot{V}O_2$, and HR values mirrored team-sport lab and field based values, verifying the external validity of the selected methodology, this protocol could potentially be used to assess intermittent sport athletes. Prospective studies should direct their focus on further differentiating the rest times between RSA testing protocols. Furthermore, female participants should be examined to determine any sex-related differences in the work-time relationship as applied to repeated sprint exercise. Finally, additional attention should be devoted to determining the changes in energy system contribution during prolonged duration repeated sprint exercise.

APPENDIX A: LIST OF TABLES

Table 1: Descriptive data for participants

	Mean		SD
Age (years)	24.1	±	3.6
Height (cm)	175.8	±	7.0
Weight (kg)	77.6	±	12.8
$\dot{V}O_{2\text{peak}}$ (L/min)	3.3	±	0.6
$\dot{V}O_{2\text{peak}}$ (ml/kg/min)	43.3	±	5.6
BF (%)	24.5	±	4.4

BF (%) = Body Fat percentage

Table 2: Comparison of each repeated sprint ability (RSA) protocol

Rest Interval	12s (n=8)		18s (n=10)		24s (n=12)		30s (n=4)		36s (n=2)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Pmax (W)	1177.358 ± 173.365		1193.338 ± 292.116		1239.464 ± 295.881		1497.238 ± 316.050		1591.625 ± 112.055	
AvePP (W)	1026.043 ± 166.396		1069.561 ± 255.395		1102.253 ± 246.317		1316.115 ± 252.588		1435.320 ± 145.508	
AveW (kJ)	4.004	± 0.617	4.258	± 0.945	4.571	± 0.918	5.348	± 0.988	5.809	± 0.958
Intervals (#)	23.250	± 12.361	34.700	± 20.478	36.250	± 25.299	21.000	± 8.287	48.000	± 42.426
TTE (s)	418.500 ± 222.492 *		832.800 ± 491.470		1090.000 ± 757.904		756.000 ± 298.315		2016.000 ± 1781.909	
TW (kJ)	96.443	± 57.358	150.670	± 105.400	164.402	± 123.206	111.762	± 49.855	258.512	± 200.475
Ave $\dot{V}O_2$ (L/min)	2.919	± 0.569	2.709	± 0.518	2.398	± 0.374	2.273	± 0.279	2.265	± 0.148
$\dot{V}O_{2peak}$ (L/min)	3.478	± 0.649	3.437	± 0.573	3.158	± 0.400	2.915	± 0.255	3.000	± 0.000
AveHR (bpm)	163.625 ± 8.400		166.100 ± 7.141		162.250 ± 10.814		161.500 ± 18.699		150.000 ± 5.657	

Pmax = Initial peak power prior to testing; AvePP = Average peak power per sprint; AveW = Average work per sprint; Intervals = number of intervals completed; TTE = Time to exhaustion; TW = Total work; Ave $\dot{V}O_2$ = Average absolute oxygen consumption; AveHR = Average heart rate *Significantly different between 12 and 36s.

Table 3: Comparison of participants who performed the same repeated sprint ability (RSA) protocols

Rest Interval	12s (n=8)		18s (n=8)		24s (n=8)	
	Mean	SD	Mean	SD	Mean	SD
Pmax (W)	1177.358	± 173.365	1141.348	± 235.844	1133.880	± 258.380
AvePP (W)	1026.043	± 166.396	1033.456	± 212.345	1023.929	± 221.828
AveW (kJ)	4.004	± 0.617	4.143	± 0.876	4.323	± 0.897
Intervals (#)	23.250	± 12.361	* 40.375	± 18.845	47.125	± 24.486
TTE (s)	418.500	± 222.492	* 969.000	± 452.274	1417.500	± 730.944
TW (kJ)	96.443	± 57.358	* 174.192	± 105.250	210.138	± 128.989
Ave $\dot{V}O_2$ (L/min)	2.919	± 0.569	* 2.778	± 0.542	† 2.478	± 0.416
$\dot{V}O_{2peak}$ (L/min)	3.478	± 0.649	3.539	± 0.591	3.268	± 0.440
AveHR (bpm)	163.625	± 8.400	166.500	± 7.819	164.625	± 10.433

Pmax = Initial peak power prior to testing; AvePP = Average peak power per sprint; AveW = Average work per sprint; Intervals = number of intervals completed; TTE = Time to exhaustion; TW = Total work; Ave $\dot{V}O_2$ = Average absolute oxygen consumption; AveHR = Average heart rate. *Significantly different between 12 and 24s. †Significantly different between 18 and 24s

Table 4: Estimated values for critical rest interval (CRI) and anaerobic working capacity (W')

Subject	CRI (s)	W' (kJ)	r^2
1	33.19	58.682	0.996
2	36.65	50.442	1.000
3	42.63	42.515	0.705
4	30.65	36.252	0.945
5	49.17	22.320	0.995
6	42.56	29.406	0.958
7	34.66	17.842	0.966
8	42.40	26.603	0.995
9	33.45	26.982.	0.968
10	45.81	26.930	1.000
11	51.74	27.282	0.976
12	32.95	73.647	0.924
Mean	39.66	36.575	0.952
SD	7.00	16.698	0.081

r^2 = Coefficient of determination

Table 5: Comparison of validation trials above and below critical rest interval (CRI)

	Above CRI (n=7)		Below CRI (n=7)	
	Mean	SD	Mean	SD
Pmax (W)	1295.61	± 421.28	1290.68	± 320.96
AvePP (W)	1154.93	± 302.50	1162.39	± 306.06
AveMP (W)	810.71	± 212.33	822.18	± 212.22
AveW (kJ)	4.78	± 1.24	4.83	± 1.22
Intervals (#)	46.71	± 22.14	38.00	± 24.09
TTE (s)	2270.43	± 941.15	* 1511.00	± 811.03
RPR	3.41	± 0.90	3.53	± 0.88
Lactate (mmol/L)	6.56	± 3.45	* 8.94	± 4.89
TW (kJ)	204.49	± 75.31	157.78	± 106.89
Ave $\dot{V}O_2$ (L/min)	1.78	± 0.26	† 2.05	± 0.36
$\dot{V}O_{2peak}$ (L/min)	2.61	± 0.43	* 2.84	± 0.48
AveHR (bpm)	138.14	± 17.51	* 151.14	± 18.46

Pmax = Initial peak power prior to testing; AvePP = Average peak power per sprint; AveMP = Average mean power; AveW = Average work per sprint; Intervals = number of intervals completed; TTE = Time to exhaustion; RPR = Rate of perceived readiness; TW = Total work; Ave $\dot{V}O_2$ = Average absolute oxygen consumption. * Significantly different from Above CRI p<0.05. † Significantly different from Above CRI p<0.001.

APPENDIX B: LIST OF FIGURES

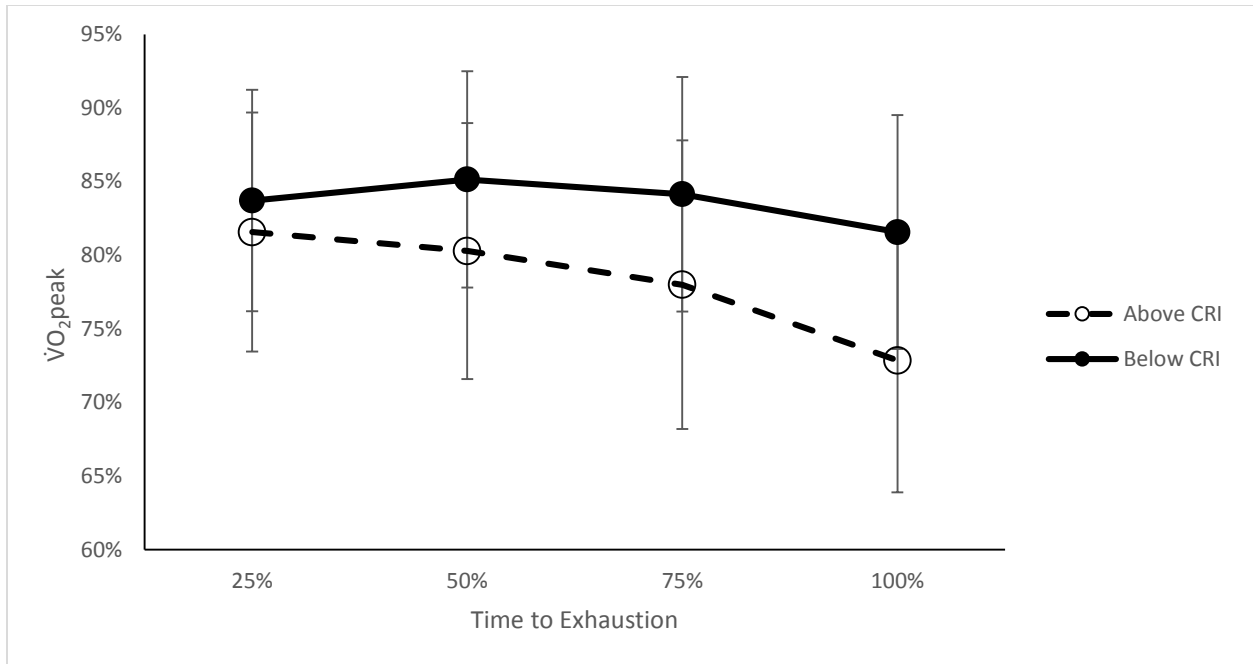


Figure 1: Maximal $\dot{V}O_2$ response during the validation trials above and below critical rest interval (CRI) relative to maximal oxygen consumption ($\dot{V}O_{2peak}$) from the graded exercise test

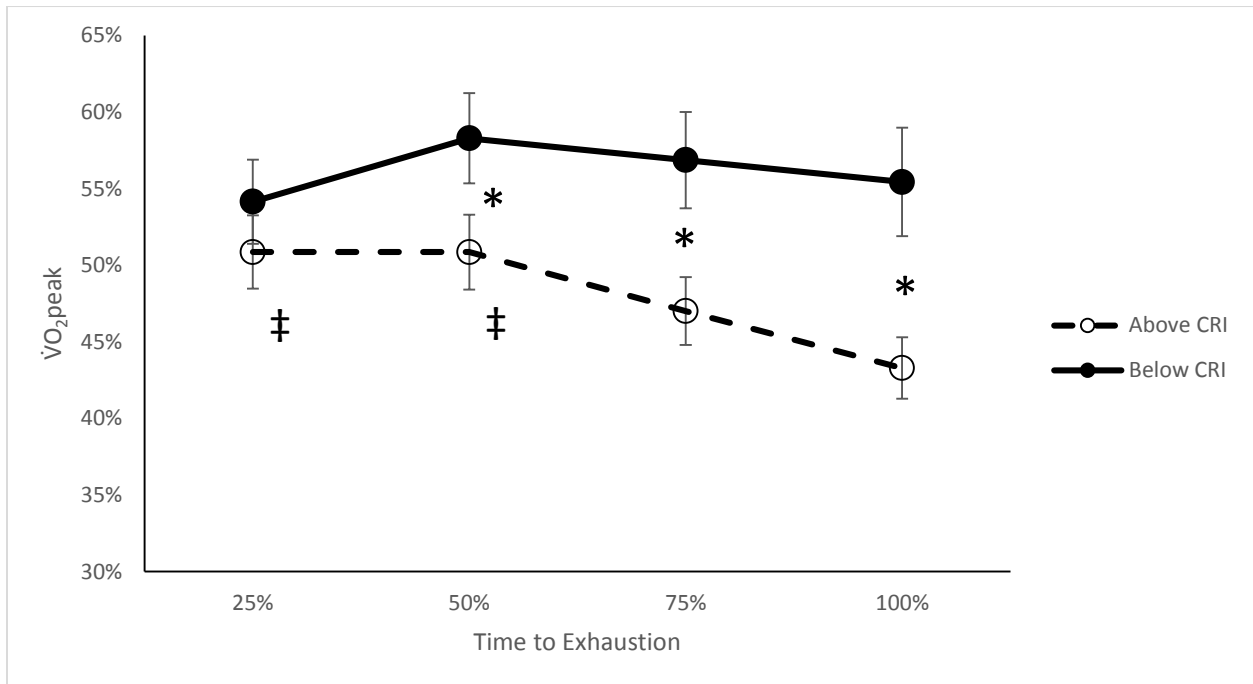


Figure 2: Minimal $\dot{V}O_2$ response during the validation trials above and below critical rest interval (CRI) relative to maximal oxygen consumption ($\dot{V}O_{2peak}$) from the graded exercise test

*Significantly different between trials ($p < 0.05$). ‡Significantly different from 100% in the above CRI trial ($p < 0.05$).

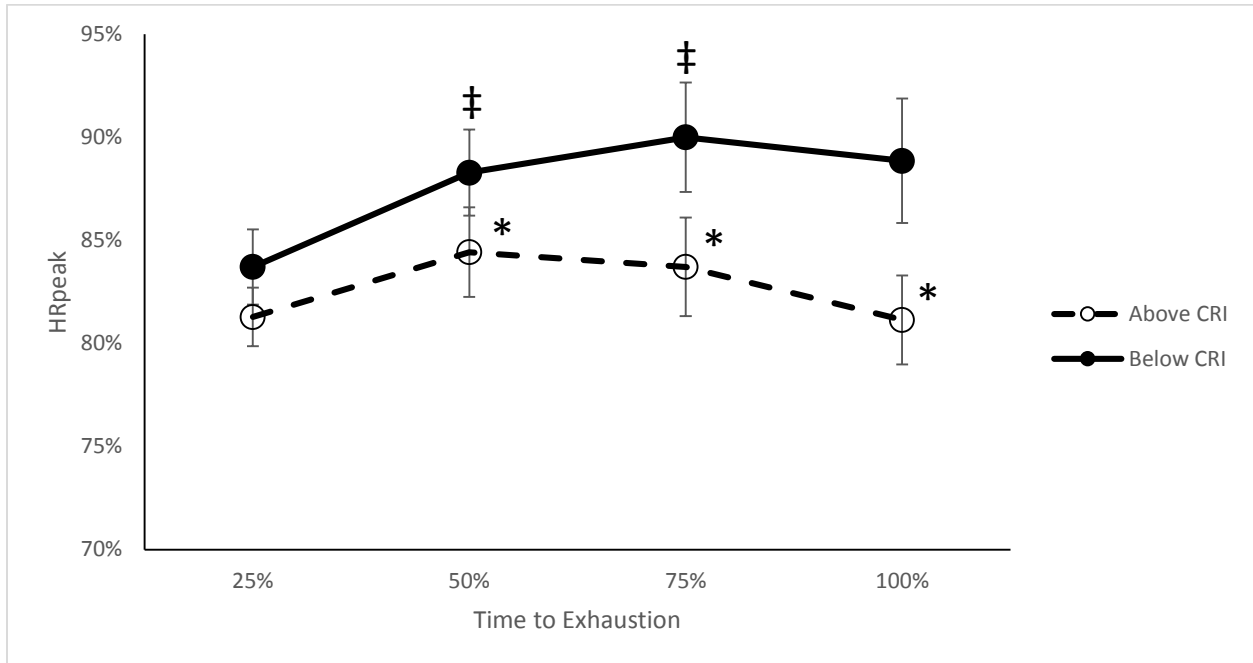


Figure 3: Maximal heart rate response during the validation trials above and below critical rest interval (CRI) relative to maximal heart rate (HRpeak) from the graded exercise test

*Significantly different between trials ($p < 0.05$). ‡Significantly different from 25% in the below CRI trial ($p < 0.05$).

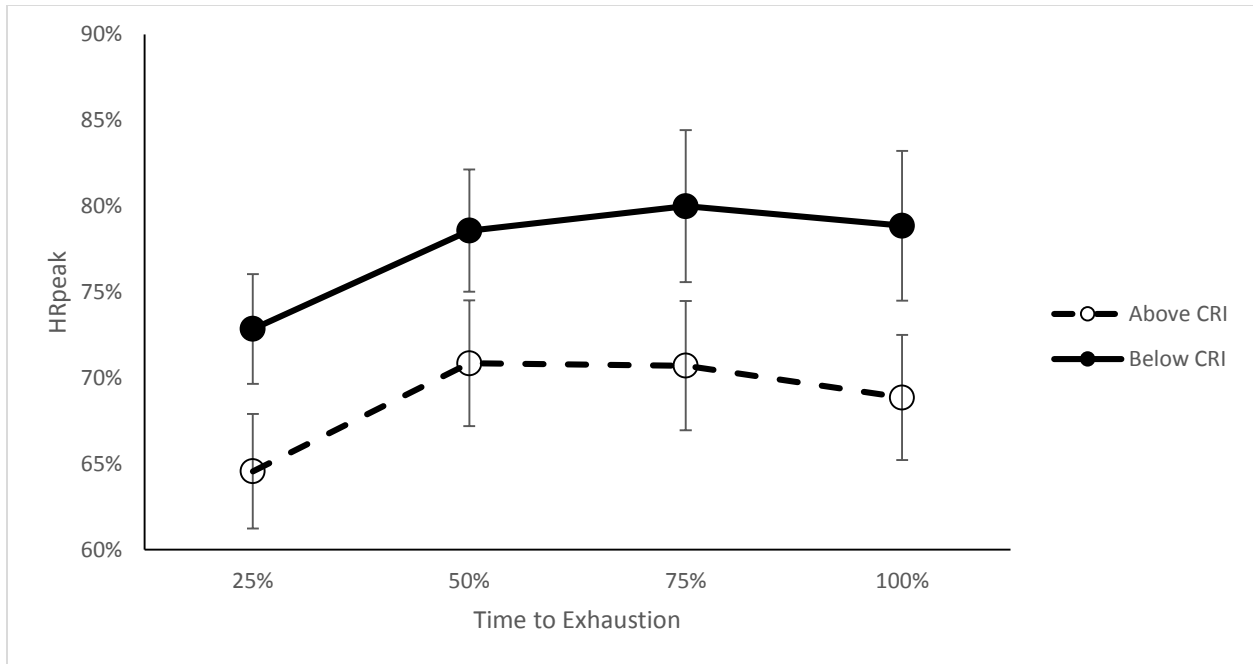


Figure 4: Minimal heart rate response during the validation trials above and below critical rest interval (CRI) relative to maximal heart rate (HRpeak) from the graded exercise test

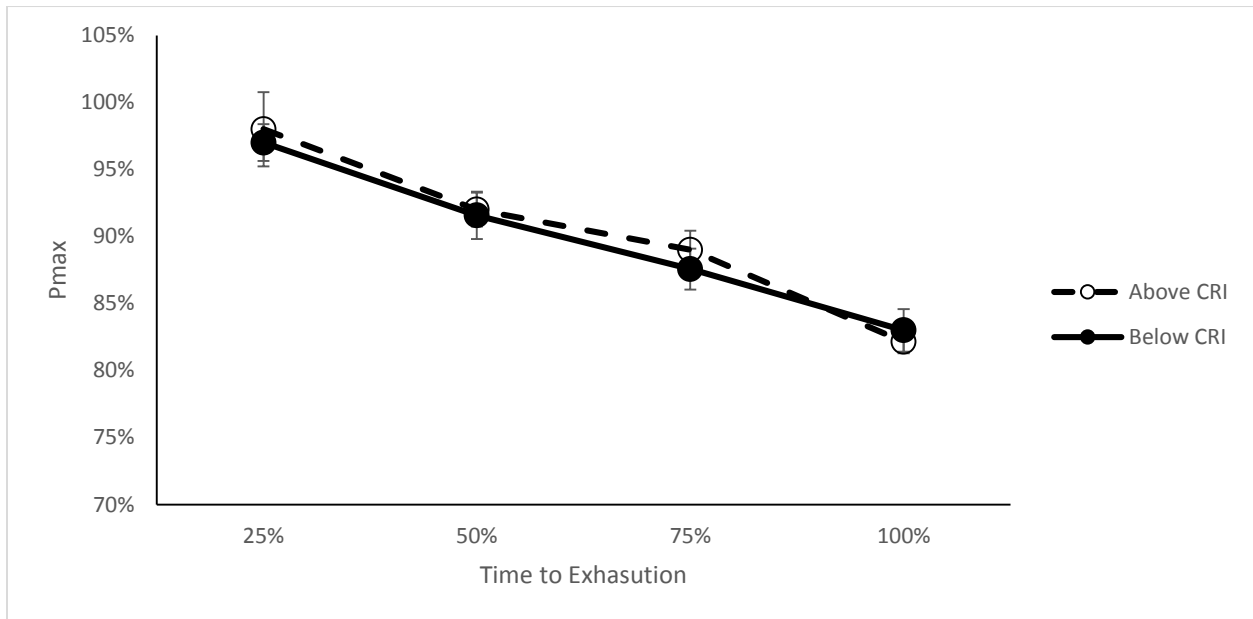


Figure 5: Peak power relative to initial maximal power (Pmax) values during the validation trials above and below critical rest interval (CRI)

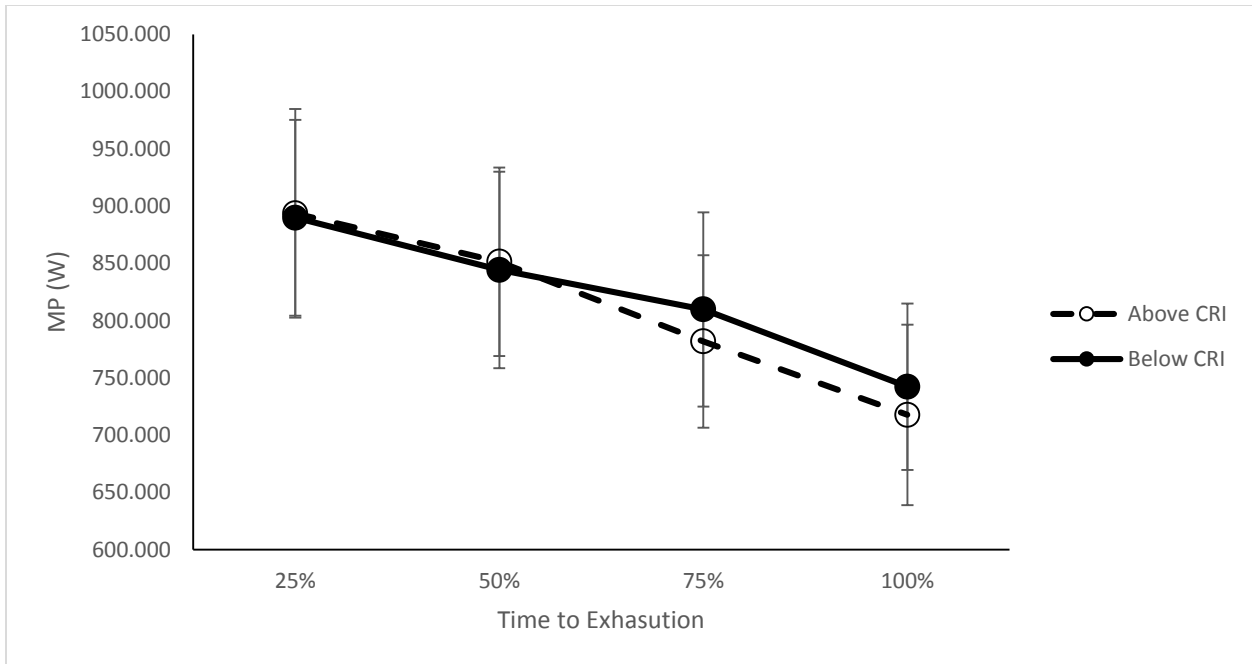


Figure 6: Mean power (MP) during the validation trials

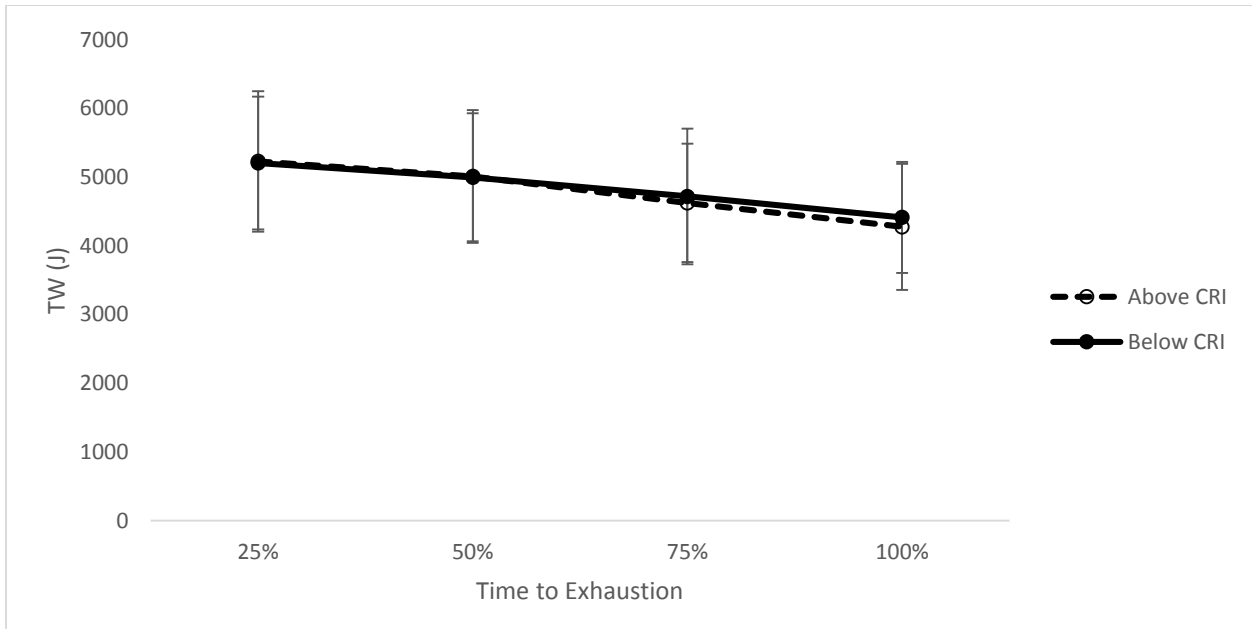


Figure 7: Average total work (TW) during the validation trials

APPENDIX C: IRB APPROVAL



University of Central Florida Institutional Review Board
Office of Research & Commercialization
12201 Research Parkway, Suite 501
Orlando, Florida 32826-3246
Telephone: 407-823-2901 or 407-882-2276
www.research.ucf.edu/compliance/irb.html

Approval of Human Research

From: **UCF Institutional Review Board
#1 FWA00000351, IRB00001138**

To: **Michael B. Lamonica and Co-PI: David Fukuda**

Date: **February 25, 2014**

Dear Researcher:

On 2/25/2014, the IRB approved the following human participant research until 2/24/2015 inclusive:

Type of Review: UCF Initial Review Submission Form
Project Title: Determination of the critical rest interval from repeated sprint ability testing during cycle ergometry
Investigator: Michael B Lamonica
IRB Number: SBE-14-09957
Funding Agency:
Grant Title:
Research ID: NA

The scientific merit of the research was considered during the IRB review. The Continuing Review Application must be submitted 30 days prior to the expiration date for studies that were previously expedited, and 60 days prior to the expiration date for research that was previously reviewed at a convened meeting. Do not make changes to the study (i.e., protocol, methodology, consent form, personnel, site, etc.) before obtaining IRB approval. A Modification Form **cannot** be used to extend the approval period of a study. All forms may be completed and submitted online at <https://iris.research.ucf.edu>.

If continuing review approval is not granted before the expiration date of 2/24/2015, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

Use of the approved, stamped consent document(s) is required. The new form supersedes all previous versions, which are now invalid for further use. Only approved investigators (or other approved key study personnel) may solicit consent for research participation. Participants or their representatives must receive a copy of the consent form(s).

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

On behalf of Sophia Dziegielewski, Ph.D., L.C.S.W., UCF IRB Chair, this letter is signed by:

A handwritten signature in black ink that reads "Joanne Muratori". The signature is written in a cursive style with a large, looping initial "J".

IRB Coordinator

APPENDIX D: INFORMED CONSENT



Determination of critical rest interval from repeated sprint ability testing

Informed Consent

Principal Investigator(s): Michael La Monica
David H. Fukuda, Ph.D.

Sponsor: N/A

Investigational Site(s): University of Central Florida
College of Education and Human Performance
Sport and Exercise Science

Introduction: Researchers at the University of Central Florida (UCF) study many topics. To do this we need the help of people who agree to take part in a research study. You are being invited to take part in a research study that will include 20 men at UCF. You have been asked to take part in this research study because you are an active young adult who routinely participates in recreational training. You must be between 18 and 35 years of age to be included in this research study.

The principal investigators conducting the research are Michael La Monica, and Dr. David H. Fukuda. They will be supported by Dr. Jeffrey R. Stout, Dr. Jay R. Hoffman, and Dr. Maren S. Fragala (Sport and Exercise Science in the College of Education).

What you should know about a research study:

- Someone will explain this research study to you.
- A research study is something you volunteer for.
- Whether or not you take part is up to you.
- You should take part in this study only because you want to.
- You can choose not to take part in the research study.
- You can agree to take part now and later change your mind.
- Whatever you decide it will not be held against you.
- Feel free to ask all the questions you want before you decide.

Purpose of the research study: There are three objectives to this study: 1) Examine the amount of work you can accomplish before fatigue during cycling. 2) Estimate how long of a rest period you need from the results of interval testing with various work-to-rest ratios during cycling. 3) Justify whether your calculated rest interval during cycling is accurate by measuring the amount of oxygen you consume during intermittent cycling.

Inclusion and Exclusion Criteria

Inclusion criteria:

- Recreationally trained individuals that currently exercise two to five times per week.
- Individuals with a VO_{2max} above 35ml/kg/min
- Free of any physical limitations as determined by the Confidential Medical and Activity History questionnaire and/or PAR-Q
- Between the ages of 18 and 35

Exclusion criteria:

- Inability to perform physical exercise, as determined by the Confidential Medical and Activity History questionnaire and/or PAR-Q
- Any chronic illness that causes continuous medical care

Testing location and time requirements:

All testing will be conducted in the Human Performance Lab (HPL) in the College of Education and Human Performance building at the University of Central Florida. All

measures and tests are conducted for research purposes only. The results will not be used to diagnose any illness or disease and will not provide any meaningful information to your physician.

Time requirements: Participation in this study will require seven visits (approximately 5 and a half hours) to the Institute of Exercise Physiology and Wellness Human Performance Laboratory. Those seven visits will last approximately 5 weeks with 2 sessions per week, with each session lasting approximately 30-75 minutes.

What you will be asked to do in the study:

All participants will undergo an initial visit and six testing visits. The initial visit will consist of filling out a PAR-Q and Confidential Medical and Activity questionnaire as well as signing an Informed Consent. Performance testing will be conducted using a cycle ergometer. Heart rate will be tracked through each testing session using a heart rate monitor. Body composition testing will be completed using bioelectrical impedance analysis. Each testing session will be separated by a minimum of 24-48 hours. The six testing sessions will include: the graded exercise test (GXT) visit, used to assess $\dot{V}O_{2peak}$ and peak power output, three repeated sprint ability test (RSA1, RSA2, & RSA 3) visits, and two critical rest interval validation (CRI+ & CRI-) visits, consisting of time-to-exhaustion trials above and below the calculated critical rest interval.

Scheduled Visits:

Initial Visit: You will be asked to read and sign this consent form before any study-related procedures are performed. You will be asked to refrain from consuming food for four hours prior to the visit and to be normally hydrated. During this first visit, the following will be done:

- Complete the Physical Activity Readiness Questionnaire (PAR-Q)
- Complete the self-reported medical and activity history questionnaire
- Your age, race and gender will be collected
- Your body measurements (height, weight) and body composition will be measured

- You will be asked to remove your footwear, including socks, and lie supine on a padded table. Resting electrodes will be placed on your hands, thighs, and feet. A minute electrical current will be conducted through your body to determine body composition. These machines are widely-used commercial devices that are FDA approved.
- This session will last approximately 30 minutes.

Testing Visit 1: The second visit will take place at least 24 hours following the initial visit. On this visit:

- You will be asked to perform a VO₂ peak test, which will include cycling at 60-80 revolutions per minute against progressively increasing resistance until you can no longer continue. Expired gases will be collected via a mask to determine oxygen uptake.
- You will also be asked perform approximately 10 submaximal and maximal cycling sprints lasting 6 seconds with 24 seconds of rest between each sprint.

This visit will last approximately 40 minutes.

Testing Visit 2, Visit 3, and Visit 4: These visits will take place no sooner than 48hrs following the previous testing visit. On these visits:

- You will perform a 4-minute warm-up at a self-selected resistance on the cycle ergometer interspersed with 4 submaximal sprints lasting 6 seconds followed by 3 6-second maximal sprints at a workload relative to your body weight to establish your maximal power output. Following a 5-minute rest, you will begin a series of maximum effort 6-seconds sprints against a workload relative to your body weight interspersed by 24 seconds of rest (Visit 2). During subsequent visits, the rest period will be changed by the researchers to alter the number of sprints that you can complete to allow for exercise time between 60 and 600 seconds. You will be verbally encouraged throughout the sprints and will be asked to continue until you cannot attain 80-85% of your maximal power output for 2 consecutive sprints. In addition, VO₂ values will be recorded continuously and require you to wear a one way valve mask that covers your nose and mouth.
- These visits will last approximately 30-75 minutes.

Testing Visit 5 & Visit 6: These visits will take place no sooner than 48hrs following the previous testing visit. On these visits:

- You will be asked to complete 6-second maximal sprints against a workload relative your body weight interspersed by rest periods of unloaded cycling equivalent to a rest

interval determined by Testing Visits 2-4 plus an additional 5-10%. The test will end after 45 minutes of exercise or when you have two consecutive sprints where power output values are less than 80-85% of the maximal power output, if it occurs before 45 minutes. Expired gases will be collected via a mask to determine oxygen uptake in the same manner as during Testing Visit 1. Additionally, heart rate values will be recorded following every set of 5 sprints and blood lactate concentrations will be determined following every set of 10 sprints.

- The blood lactate measurements will require that your finger be pricked prior to analysis. Blood lactate is a way to measure blood acidity and indicate how intense a given workout is. Possible minor discomfort can be associated with this as a small thin disposable needle will pierce the tip of your finger. Blood lactate will occur after every 10 sprints and the finger will be bandaged in between finger pricks. Only one drop of blood will be needed for each lactate analysis.
- These visits will last approximately 30-75 minutes

Funding for this study: This research study is not being funded.

Risks:

There is a possible risk of muscle strain or injury during the exercise test protocol. Participants' physical risks will be minimized by having each testing session conducted by qualified investigators. All testing procedures will be done in a controlled manner. All additional research staff members directly involved with testing of the participants are familiar with the American College of Sports Medicine standards and protocols for exercise testing and emergency management. Rise in heart rate and blood pressure associated with exercise may also occur. Blood lactate analysis will be required more than once during the last two trials of the study. During blood lactate analysis the subject's finger will be cleaned with an alcohol wipe and then pricked by a small thin disposable needle from the lactate analyzer in order to draw one drop of blood for analysis. Although unlikely, there is a small risk of infection associated with blood lactate finger pricks. Risk of infection is unlikely. Participants will also be asked to perform multiple exercise tests. During these tests they will be asked to give maximal effort which may lead to some discomfort. After completion of these tests they may experience feelings of muscle soreness and fatigue. To reduce the chance of these risks, preliminary screenings are evaluated. Participants will be asked to wear a mask that stabilizes a one-way valve around their mouth and nose for the duration of the protocol. Additionally, all testing will be overseen by individuals certified in Cardio

Pulmonary Resuscitation (CPR) and Automated External Defibrillator (AED). An AED is located in the building where testing will occur.

You are free to withdraw from the study at any time you desire without penalty.

You should report any discomforts or injuries to one of the principal investigators Michael La Monica, 407-823-2367, lamonica@ucf.edu or Dr. David Fukuda, 407-823-0442, david.fukuda@ucf.edu. If you believe you have been harmed or experience a research-related injury please let the researcher know and if medical attention is required you will be expected to contact your own medical professional for follow-up. However, you or your insurance company will be responsible for the costs of this treatment. No funds have been set aside by The University of Central Florida to compensate you in the event of injury.

Provisions to monitor the data for the safety of participants (Required when Human Research involves more than minimal risk to participants.)

To help ensure the safety of participants, testing sessions will be supervised by a certified Health and Fitness Specialist or Certified Strength and Conditioning Specialist.

Benefits

There are no direct benefits to participants.

Compensation or payment:

No compensation will be provided for completion of this study.

Confidentiality: The results of this study will be published as a group as part of a scientific publication. No individual results will be published or shared with any person or party. All information attained from the medical and activity questionnaires or performance tests will be held in strict confidence. Individual results will remain confidential and only be relayed to the participant upon request. All medical and activity questionnaires, as well as data collection sheets will be kept in a locked cabinet during and following the study. All information will be destroyed five years from the end of the study and not used for other research purposes. Participant folders will be marked with an I.D. number to protect against a breach of confidentiality, and the ID number will be removed upon disposal.

Study contact for questions about the study or to report a problem: If you have questions, concerns, or complaints, or think the research has hurt you, please contact Michael La Monica

or Dr. David Fukuda, Human Performance Laboratory, Sport and Exercise Science (407) 823-2367 or by email at lamonica@ucf.edu or david.fukuda@ucf.edu.

IRB contact about your rights in the study or to report a complaint: Research at the University of Central Florida involving human participants is carried out under the oversight of the Institutional Review Board (UCF IRB). This research has been reviewed and approved by the IRB. For information about the rights of people who take part in research, please contact: Institutional Review Board, University of Central Florida, Office of Research & Commercialization, 12201 Research Parkway, Suite 501, Orlando, FL 32826-3246 or by telephone at (407) 823-2901. You may also talk to them for any of the following:

- Your questions, concerns, or complaints are not being answered by the research team.
- You cannot reach the research team.
- You want to talk to someone besides the research team.
- You want to get information or provide input about this research.

Withdrawing from the study:

You have the right to discontinue participation without penalty, regardless of the status of the study. Your participation in the study may also be terminated at any time by the researchers in charge of the project. This could be based upon your refusal to follow study instructions or follow the study protocol.

DO NOT SIGN THIS FORM AFTER THE IRB EXPIRATION DATE BELOW

Name of participant

Signature of participant

Date

Signature of person obtaining consent

Date

Printed name of person obtaining consent

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