CHANGES IN TIME TO REACH VO$_2$MAX IN SUBSEQUENT HIGH-INTENSITY INTERVALS

A Thesis

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by

Adam James Switters

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by

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__________________________, Graduate Coordinator
Daryl Parker, Ph.D

Department of Kinesiology
Abstract

of

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Adam James Switters

Introduction

During high-intensity exercise, oxygen uptake increases until maximal oxygen consumption (VO₂max) is reached. The rate at which the body uptakes oxygen can be described through VO₂ kinetics. When high-intensity exercise is preceded by an additional bout of high-intensity exercise, VO₂ kinetics are altered so that VO₂max is achieved sooner. Therefore, it is possible that VO₂ kinetics are further altered by subsequent bouts of high-intensity exercise.

Purpose

To investigate the time to reach VO₂max during subsequent intervals at pVO₂max lasting 60% Tmax in well-trained cyclists.

Methods

Twelve male cyclists completed a graded exercise test (GXT) to determine their pVO₂max, followed by a time to fatigue test later that same day to determine their
Tmax. After 7 days, subjects returned and completed 5 intervals at pVO$_{2\text{max}}$ for a duration of 60% Tmax. In between intervals, subjects pedaled at a low load (20W) for a duration equal to their interval duration. Expired air and heart rate (HR) was recorded as 20-second averages. Analysis of peak values (VO$_2$, HR, and VE) between the GXT and interval trials was completed with a paired t-test. Analysis of interval variables (time to reach VO$_2\text{max}$, peak VO$_2$ HR, VE, and RER) was completed with a one-way repeated measures ANOVA. A p-level of <0.05 was used for significance. When significance was found a *Tukey post hoc* test was used for comparisons.

**Results**

There was a significant increase in peak values of VO$_2$ and VE in the interval trials compared to the GXT (70.5 ml/kg/min$^{-1}$ from 67.8, and 183.2 L/min from 168.7 respectively). There was a significant decrease in time to reach VO$_2\text{max}$ (63.37% to 32.97%) over the duration of the intervals, with intervals 1 and 2 showing significant differences from interval 5. Peak VO$_2$ showed a significant increase (63.2 ml/kg/min$^{-1}$ to 71.23) over the duration of the intervals, with intervals 1 and 2 showing significant differences from interval 5. Both VE (144.6 L/min to 181.1) and HR (171.4 bpm to 183.8) showed significant increases over the duration of the interval, with significant changes seen in intervals 1, 2 and 3 compared to interval 5. Only the peak RER (1.45) in the interval 1 was significantly different from the last interval (1.25). In addition, only the peak RER achieved during the interval 1 was significantly higher than the peak RER from the GXT (1.15).
Conclusion

The findings from this study support the theory that VO₂ kinetics in a heavy exercise bout are altered to allow VO₂max to be reached sooner when that exercise is preceded by another heavy exercise bout. In addition, our data supports the idea that VO₂ kinetics will continue to be altered in a further subsequent bout, but will reach a point where additional bouts have no affect on the time to reach VO₂max.

_______________________, Committee Chair
Daryl Parker, Ph.D

_______________________
Date
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I would first like to thank my amazing and loving wife, Sonia. Without her patience and support, none of this would have been possible. It’s been tough with both of us in graduate school at the same time, but we each act as each other’s steady rock. I love you to the moon and back.

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Thank you to my intern Martin as well as my fellow graduate students, Shannon and Nick. We went through trials and tribulations together. We laughed, we joked and we complained (probably more often than we would like to admit. Couldn’t have made it through this program with you guys.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Acknowledgements</th>
<th>viii</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of Tables</td>
<td>xii</td>
</tr>
<tr>
<td>List of Figures</td>
<td>xiii</td>
</tr>
<tr>
<td>Chapter dialtion</td>
<td></td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Background</td>
<td>1</td>
</tr>
<tr>
<td>Purpose</td>
<td>3</td>
</tr>
<tr>
<td>Significance of Thesis</td>
<td>3</td>
</tr>
<tr>
<td>Hypothesis</td>
<td>3</td>
</tr>
<tr>
<td>Definition of Terms</td>
<td>4</td>
</tr>
<tr>
<td>2. REVIEW OF LITERATURE</td>
<td>5</td>
</tr>
<tr>
<td>Interval Training</td>
<td>5</td>
</tr>
<tr>
<td>Benefits of interval training</td>
<td>6</td>
</tr>
<tr>
<td>Interval duration</td>
<td>7</td>
</tr>
<tr>
<td>pVO₂max and vVO₂max</td>
<td>9</td>
</tr>
<tr>
<td>History of vVO₂max</td>
<td>9</td>
</tr>
<tr>
<td>Influence of different protocols on vVO₂max</td>
<td>11</td>
</tr>
<tr>
<td>Tmax</td>
<td>12</td>
</tr>
<tr>
<td>Individual variability in Tmax</td>
<td>14</td>
</tr>
<tr>
<td>Tmax as an interval duration</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>ix</td>
</tr>
</tbody>
</table>
Time to Reach VO$_2$max.................................................................34
  Mechanisms............................................................................34
Exercise Prescription .....................................................................37
  Peak VO$_2$, HR, and VE...........................................................37
RER .................................................................................................38
  GXT vs. Intervals ........................................................................39
  Implications of findings.............................................................40
Conclusion ..................................................................................40
Appendix A. Health History and Training Questionnaire..................42
Appendix B. Informed Consent.......................................................46
References ..................................................................................49
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Tables</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Tmax at the velocity or power associated with 100% VO$_2$max</td>
<td>13</td>
</tr>
<tr>
<td>2. Descriptive GXT means (±SD) with relative percent of peak values (n = 11)</td>
<td>25</td>
</tr>
<tr>
<td>3. Comparison of peak values from GXT and Intervals</td>
<td>26</td>
</tr>
<tr>
<td>4. Means values from interval trials</td>
<td>28</td>
</tr>
<tr>
<td>Figures</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1.</td>
<td>Peak RER presented for GXT and intervals</td>
</tr>
<tr>
<td>2.</td>
<td>VO\textsubscript{2} and RER values presented over the course of the interval trials</td>
</tr>
<tr>
<td>3.</td>
<td>Time to reach VO\textsubscript{2}max presented for each interval</td>
</tr>
<tr>
<td>4.</td>
<td>Peak VO\textsubscript{2} presented for each interval</td>
</tr>
<tr>
<td>5.</td>
<td>Peak VE presented for each interval</td>
</tr>
<tr>
<td>6.</td>
<td>Peak HR presented for each interval</td>
</tr>
</tbody>
</table>
Chapter 1
INTRODUCTION

Background

Interval training has existed since the mid 19th century, but first became popularized in the 1950’s by Olympic champion Emil Zapotek. Interval training consists of exercising in alternating bouts of high-intensity and low-intensity exercise and is thought to be a method of training at high levels of intensity for longer periods of time compared to steady exercise. This type of training taxes the cardiorespiratory system, and when the intensity is strenuous enough, enhances the body’s ability to maximally uptake oxygen.

The amount of oxygen that an athlete is maximally able to consume ($\text{VO}_2\text{max}$) during exercise is theorized to be a predictor of aerobic performance (Taylor, Buskirk, & Henschel, 1955). Interval training allows athletes to stay at an exercise intensity corresponding to their $\text{VO}_2\text{max}$ longer than a single continuous bout of exercise, and is thus theorized as a method to increase $\text{VO}_2\text{max}$ (Christensen, Hedman, & Saltin, 1960). Optimum training for cardiorespiratory fitness is thought to occur at intensities between 90 and 100% $\text{VO}_2\text{max}$ (Christensen et al., 1960). It appears that through interval training at very high percentages of $\text{VO}_2\text{max}$ that an athlete will be able to optimally increase their athletic performance.

There is an increase in both performance and $\text{VO}_2\text{max}$ when intervals are structured so that $\text{VO}_2\text{max}$ is attained during an interval (Hill & Rowell, 1997). One common interval type that elicits this response for cyclists requires subjects to ride at an
intensity corresponding to \( p\text{VO}_2\text{max} \); the power that minimally elicits \( \text{VO}_2\text{max} \) during a graded exercise test (GXT). As opposed to a set interval duration that is universal among all subjects, an ideal duration is thought to be related to duration that \( p\text{VO}_2\text{max} \) can be maintained, otherwise known as \( \text{Tmax} \).

Several studies have found that a duration of 60% of \( \text{Tmax} \) is required to minimally elicit \( \text{VO}_2\text{max} \) (Billat, 2001; Esfarjani & Laursen, 2007; Hill & Rowell, 1996; Smith, McNaughton, & Marshall, 1999). In running, the minimal velocity that elicits \( \text{VO}_2\text{max} \) during a GXT is known as \( v\text{VO}_2\text{max} \). A 2003 study by Smith, Coombes and Geraghty showed an improvement in 3000m running times with a training program consisting of intervals at \( v\text{VO}_2\text{max} \) for 60% \( \text{Tmax} \) compared to intervals at 70% \( \text{Tmax} \). From this, it is assumed that an interval program might be most beneficial when the duration of the interval allows a participant to minimally reach \( \text{VO}_2\text{max} \) followed immediately by recovery. However, it is unclear if the 60% \( \text{Tmax} \) relationship is consistent from interval to interval.

During intense exercise, the rate at which the body consumes oxygen is described by a \( \text{VO}_2 \) kinetics profile. Following an intense bout of exercise, it takes approximately 45 minutes for a subject’s \( \text{VO}_2 \) kinetics to return to a normal profile (Burnley, Doust, & Jones, 2006). A recovery duration shorter than this leads to an altered \( \text{VO}_2 \) kinetics profile that is characterized by an accelerated consumption of oxygen known as a “priming” effect (Burnley, Davison, & Baker, 2011).

A 2001 study looked at how a previous bout of intense exercise changed \( \text{VO}_2 \) kinetics in a following bout of intense exercise (Burnley, Doust, Carter, & Jones, 2001).
Participants exercised on a cycle ergometer for 6 minutes at a power output halfway between their lactate threshold (LT) and VO$_2$max, followed by 6 minutes of recovery at 20 watts (W). They found that during the second bout of exercise, there was a change in VO$_2$ kinetics that led to an overall acceleration of O$_2$ uptake. This led to a significant decrease in the time to reach VO$_2$max in the second exercise bout. However, it is unclear if this pattern will continue in further subsequent heavy exercise bouts.

**Purpose**

The purpose of this study was to investigate the time to reach VO$_2$max during subsequent intervals at pVO$_2$max lasting 60% Tmax in well-trained cyclists.

**Significance of Thesis**

The results of the study by Burnley et al. in 2001 give basis to the idea that a previous bout of intense exercise affects the VO$_2$ kinetics of the following bout. Theoretically then, multiple bouts of intense exercise could further alter this effect. There is a gap in the literature that needs to be fulfilled to better understand the physiological mechanisms that possibly alter VO$_2$ kinetics during subsequent high-intensity intervals.

**Hypothesis**

1. There will be a significant decrease in the time required to reach VO$_2$max during each subsequent interval
2. Subjects will reach VO$_2$max near 60% of their time to fatigue test
3. The will be no significant difference in peak VO$_2$, HR, respiratory exchange ratio (RER) and ventilation (VE) attained during the GXT and interval trials.
4. There will be no significant difference in peak VE, HR, VO$_2$, and RER
between intervals

**Definition of Terms**

\( \tau \): VO\(_2\) time constant

*Aerobic*: Metabolism that converts O\(_2\) to energy

*GET*: Gas exchange threshold. The breakpoint in values of VCO\(_2\) and VO\(_2\)

*uptake*

*GXT*: Graded exercise test

*[La]'*: Lactate concentration

*LT*: Lactate threshold. The break point in lactate accumulation during a GXT

*Interval*: Alternating bouts of heavy, moderate or low intensity exercise

*PPO*: Peak power output from a GXT

*Phase I*: First phase of VO\(_2\) kinetics attributed to increased venous return

*Phase II*: Primary phase of VO\(_2\) kinetics due to increases in oxidative metabolism

*Phase III*: Last phase of VO\(_2\) kinetics due to the VO\(_2\) slow component

*RER*: Respiratory exchange ratio (VCO\(_2\)/VO\(_2\))

*RCP*: Respiratory Compensation Point (point at there is an upward inflection in VEVCO\(_2\) and VEVO\(_2\))

*Tmax*: Duration an exercise intensity can be maintained

*VE*: Ventilatory volume expressed as a flow rate in L/min

*VO\(_2\)max*: Maximal volume of oxygen consumed by the body expressed as a flow rate
Chapter 2

REVIEW OF LITERATURE

This review of literature will attempt to provide a rationale behind continued study of high-intensity intervals. Major subtopics will include the history of interval training, an evaluation of $vVO_2\max$ and $pVO_2\max$ as exercise intensities, the use of $T_{max}$ as an interval duration, and the effects of prior exercise on subsequent bouts of exercise.

**Interval Training**

Interval training involves alternating bouts of exercise at a high-intensity with recovery periods at low-intensity or rest. During the 1920’s and 1930’s, the Finish runner, Pavoo Nurmi, used interval training to run at a velocity superior to what he could maintain for his 5000m running pace. He interspersed runs of 400m at 24km/h with recovery periods of 10-20km/h (Billat, 2001). During the 1950’s Olympic champion Emil Zapotek truly popularized interval training with sessions of up to 100 x 400m intervals with 200m of jogging in between. In 1959, interval training was first published in a scientific journal when the specific interval training program of runner Siegfried Hermann was reported (Reindell & Roskamm, 1959).

In 1976, Saltin, Essen and Pedersen sought to define interval training. They reported that interval training should have the following characteristics:

(i) *Intensity* defined as the average power output

(ii) *Time-ratio* for the high and low exercise duration
(iii) The *Amplitude* as the ratio between the intensity between the different exercise periods

(iv) *Duration* and *Distances* of the high and low-intensity exercise.

**Benefits of interval training.** Babineau and Leger (1997) believed that interval training should be a regular part of an athlete's training regimen as it was better tolerated than a single maximal effort. As little as one session of interval training a week can significantly improve VO$_2$max in both trained and untrained subjects (Berthoin, Manteca, Gerbeaux, & Lensel-Corbeil, 1995; Billat, Flechet, Petit, Muriaux, & Koralsztein, 1999; Smith et al., 1999). High-intensity interval training has also been shown to be an effective way of increasing VO$_2$max (Tabata et al., 1997).

There is reason to believe that submaximal training will not improve endurance performance once an athlete has reached a VO$_2$max above 60 ml/kg/min. Londree (1997) completed a meta-analysis comparing the performance increases of both trained and untrained athletes participating in continuous training programs at an intensity corresponding to an athlete's ventilatory threshold (VT) or lactate threshold (LT). He found that continuous training at submaximal levels did not elicit increases in endurance performance in highly trained athletes. He did note however that highly trained athletes responded beneficially to high-intensity training.

High-intensity interval training has been demonstrated to increase running performance in 3km and 10km runs, as well as 40km TT's in cycling (Acevedo & Goldfarb, 1989; Laursen, Shing, Peake, Coombes, & Jenkins, 2002; Smith et al., 2003; Smith et al., 1999; Westgarth-Taylor et al., 1997). While examining the possible
explanations for interval training performance increases could comprise it’s own review of literature, pertinent reasons include improvements in oxygen delivery to the exercising muscles due to increases in stroke volume (Rowell, 1993), improvements in heat tolerance (Pandolf, 1978), improvement in the body’s ability to produce and utilize ATP (MacDougall et al., 1998), and increased skeletal muscle buffering capacity (Stepto, Hawley, Dennis, & Hopkins, 1999). In short, high-intensity interval training elicits several physiological adaptations to increase endurance performance that are not matched by continuous submaximal training.

**Interval duration.** A major proponent of interval training is the ability to stay at a very high-intensity or a high percentage of VO$_2$\text{max} for a long duration through the use of interspersed rest periods. The duration of intervals varies in literature with interval length ranging from 10 seconds to 8 minutes. Subsequently, there is much debate as to the ideal interval duration.

Astrand and colleagues (1961) theorized that interval durations of 2 minutes with a 2 minute rest was appropriate for intervals. This was supported by MacDougall and Sale (1981) who believed that 30 second intervals with a 30 second rest were inadequate for stressing the aerobic system compared to 2-3 minutes intervals. In 1984, Daniels et al. suggested that bouts of 3-5 minutes were considered optimal for training the aerobic system. The VO$_2$ response of an interval-training program of repeated bouts of 30 seconds intense exercise (100% vVO$_2$\text{max}) with 30 seconds active recovery (50% vVO$_2$\text{max}) was reported by Billat et al. in 2001. They found that participants were able to stay at VO$_2$\text{max} even during the recovery period from the 5$^{th}$ interval all the way to the
last interval (18th). This allowed her participants to stay at VO\textsubscript{2}max for over 10 minutes continuously and contradicted the ideas of MacDougal and Sale (1981).

Cycling is primarily an endurance-based sport, so the ability to improve endurance-based performance is essential. A 1999 study compared several different interval durations and intensities [based on peak power output (PPO)] on 40km TT performance (Stepto et al., 1999). The study compared interval sessions of 12 x 30 seconds at 175% PPO, 12 x 1 min at 100% PPO, 12 x 2 min at 90% PPO, 8 x 4 min at 90% PPO, 8 x 4 min at 85% PPO, and 4 x 8 min at 80% PPO. The found a curvilinear relationship between training intensity and subsequent change in 40km TT performance, with a predicted maximum enhancement in performance with workouts ranging from 3-6 minutes in length at 85% PPO. A similar study also investigated several different interval training programs on 40km TT performance, but used 60% Tmax as the interval duration for 2 of their interval protocols (Laursen et al., 2002). Average Tmax for the participants was 241 seconds ± 21, leading to an average interval time ~ 144 seconds. They saw a significant increase in 40km TT performance in the 8 x 60% Tmax at 100% pVO\textsubscript{2}max group compared to the 12 x 30 sec at 175% pVO\textsubscript{2}max group. Interval bouts ranging from 2-6 minutes appear to be ideal for maximizing endurance-based performance in cyclists. Further insight into using Tmax as an interval duration will be discussed later on.

There have been few studies on the optimization of the recovery duration between intervals. Babineau and Leger (1997) highlighted that most endurance training programs use a work to rest ratio of either 1:1 or 1:2. Laursen et al. (2002) used a 1:2 ratio and a percentage of maximal HR (65%) as recovery durations. For VO\textsubscript{2} kinetics to return to
normal for an interval bout succeeding a prior intense, it could take as long as 45 minutes of passive recovery (Burnley et al., 2006). Due to its ease and the use of effective time management, most endurance athletes choose a 1:1 or 1:2 work to rest ratio.

**pVO$_2$max and vVO$_2$max**

There is a known correlation between aerobic performance and VO$_2$max (Taylor et al. 1955). High-intensity intervals have the property of eliciting VO$_2$max, or very high percentages of VO$_2$max. These intervals ability to maximally stress oxygen uptake and oxygen utilization have proven to be a stimulus for increasing VO$_2$max (Laursen & Jenkins, 2002; Midgley & Mc Naughton, 2006). Using a GXT, we are easily able to determine an athlete’s VO$_2$max, and more importantly, their vVO$_2$max and pVO$_2$max.

**History of vVO$_2$max.** There have been several different names for the velocity that minimally elicits VO$_2$max, and even more methods used to determine this value. It was first coined in 1975 using the term “critical power” in a study comparing the aerobic and anaerobic contributions to exercise through the evaluation of oxygen deficit (Volkov, Shirkovets, & Borilkevich, 1975). That study used a GXT on a treadmill that increased 1m/s every 3 minutes until fatigue. The critical speed corresponded to the velocity at which VO$_2$max was initially reached.

In 1984, Daniels et al. used the term velocity at VO$_2$max, abbreviated vVO$_2$max, to describe a value that combined both VO$_2$max and running economy. He determined vVO$_2$max through extrapolating a linear regression curve of four submaximal VO$_2$max tests with a treadmill VO$_2$max test. Noakes (1988) and Daniels et al. (1984) agreed that...
this value was useful in describing increases in performance without corresponding increases in VO\textsubscript{2}max.

di Prampero (1989) defined V\textsubscript{am} as the maximal speed that could be maintained under aerobic conditions. He calculated the energy cost (C) as the ratio of the steady state VO\textsubscript{2} above the baseline VO\textsubscript{2} divided by the running speed. He then calculated V\textsubscript{am} using the following equation:

\[
V\text{am} = \frac{F\text{VO}_{2}\text{max}}{C}
\]

where \(F\text{VO}_{2}\text{max}\) was the maximal fraction of VO\textsubscript{2} than could be sustained during the duration of an effort.

Two studies in the late 1980’s showed that \(v\text{VO}_{2}\text{max}\) was a better predictor of aerobic performance than VO\textsubscript{2}max (Morgan et al., 1989; T. D. Noakes, 1988). Morgan et al. took a group of runners that had a homogenous VO\textsubscript{2}max profile, and showed that \(v\text{VO}_{2}\text{max}\) was a reliable predictor of 10km running performance. They determined V\textsubscript{am} using energy expenditure similar to di Prampero, but using a 7-minute treadmill test with a slope. It was later confirmed that \(v\text{VO}_{2}\text{max}\) was a predictor of performance for all distances between 10 and 90km (T. D. Noakes, Myburgh, & Schall, 1990). This protocol involved runners running on a treadmill at 10km/h with a 1km/h increase every minute till exhaustion. Peak velocity was noted as the highest velocity that could be maintained for a whole minute. The VO\textsubscript{2}max however was measured as the highest VO\textsubscript{2} recorded during any minute, which meant that peak velocity could be higher than the velocity that minimally elicits VO\textsubscript{2}max. Noakes et al. (1990) believed that this velocity
was associated with the muscles capacity for high cross-bridge cycling and respiratory adaptations.

Billat and colleagues investigated the minimal speed that would elicit VO$_2$max in several studies in 1994 (Billat, Bernard, Pinoteau, Petit, & Koralsztein, 1994; Billat, Renoux, Pinoteau, Petit, & Koralsztein, 1994a). Runners started running at 12km/h (0% slope) and speed was increased 2km/h every 3 minutes till the runner reached 80% of their peak 3000m speed. From there, the speed was increased 1km/h every 3 minutes. vVO$_2$max was taken as the lowest running speed that minimally elicited VO$_2$max. Using this velocity, they ran time to fatigue trials to determine T$_{max}$, a factor and will be discussed later on.

**Influence of different protocols on vVO$_2$max.** As has been discussed, there have been many different protocols to determine vVO$_2$max. Although the definitions are generally homogenous (“critical power”, Vamax, vVO$_2$max, peak velocity), protocol duration and intensity can influence these values. Billat and Koralsztein (1996) examined several different methods and protocols throughout literature on the determination of vVO2max for a runner with a VO$_2$max of 70ml/kg/min, an oxygen running cost of 210ml/kg/min, and a VO$_2$ at rest of 3.5ml/kg/min. They found vVO$_2$max values ranging from 18.6km/h to 21km/h.

Hill and Rowell (1996) compared 5 different methodologies of determining vVO$_2$max (di Prampero (1986), Lacour et al. (1990), Morgan et al. (1989), Noakes (1998) and Billat et al. (1994a) in 22 women track and field athletes. They found a
significant difference (P <.0001) in the evaluation of vVO₂max among all the different methods.

A similar study compared two common GXT’s in the determination of pVO₂max using a cycle ergometer (Peiffer, Quintana, & Parker, 2005). A GXT starting at 70 watts and increasing 50 watts every 3 minutes was compared to a GXT increasing 35 watts every minute gave a significantly decreased pVO₂max value (342 ± 25 vs 387 ± 27) (p < .05).

In determining vVO₂max/pVO₂max, it’s important to consider the protocol being used and the predictive capability or use of the value. For example, Billat et al. (1996) believes that Noakes (1988) protocol for peak velocity is a better predictor of middle distance running performance compared to the method of di Prampero (1986). When it comes to performing intervals however, the changes in these values might become less significant if a percentage of Tmax is used as the interval duration, as is discussed in the next section.

**Tmax**

While there is a well-established predictive ability of vVO₂max/pVO₂max on aerobic performance, the duration that this intensity can be held, otherwise known as Tmax, is highly subjective. Usually, Tmax is determined by having an athlete exercise at a specified intensity until fatigue, with Tmax being taken as the total duration of the exercise. Table I shows the variability in the values of Tmax at 100% vVO₂max for several different populations and protocols. Billat et al. (1996) noted that Tmax values ranged from 1 minute to 12 minutes, with an average being close to 6 minutes. Of an
interesting note, studies using personal records over 800, 1500, 3000 and 5000m gave Tmax values that were closely associated with an athlete’s 3000m running PR (Lacour, Padilla-Magunacelaya, Barthelemy, & Dormois, 1990; Padilla, Bourdin, Barthelemy, & Lacour, 1992).

Table 1. Tmax at the velocity or power associated with 100% VO₂max

<table>
<thead>
<tr>
<th>STUDY</th>
<th>PARTICIPANTS</th>
<th>PROTOCOL</th>
<th>FINDINGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horvath and Michael (1969)</td>
<td>14 female college students</td>
<td>Cycle Ergometer</td>
<td>3 +/- 2min</td>
</tr>
<tr>
<td>Higgs (1973)</td>
<td>20 active college women</td>
<td>Treadmill</td>
<td>4.63min</td>
</tr>
<tr>
<td>Volkov et al. (1975)</td>
<td>4 recreational runners</td>
<td>Treadmill</td>
<td>5.4 +/- 3.25min</td>
</tr>
<tr>
<td>Leger and Boucher (1980)</td>
<td>311 runners</td>
<td>Running distance</td>
<td>7min</td>
</tr>
<tr>
<td>Lavoie and Mercier (1987)</td>
<td>5 international women rowers</td>
<td>Cycle Ergometer</td>
<td>3.83 +/- 1.11min</td>
</tr>
<tr>
<td>Lacour at al. (1990)</td>
<td>27 middle distance runners</td>
<td>Track, calculated from personal records</td>
<td>8.7min (v3000m)</td>
</tr>
</tbody>
</table>
| Padilla et al. (1992)     | 38 middle distance runners      | Track personal records    | Men: 8.4 +/- 2.1min  
                           |                               |               | Women: 7 +/- 1.2min |
| Billat et al. (1994)      | 14 male middle distance         | Treadmill                 | 6.7min +/- 1.88min |
**Individual variability In Tmax.** There still remains controversy of the reproducibility of the Tmax test intra-individually. McLellan, Cheung and Jacobs (1985) saw substantial variability in Tmax at 80% $\text{vVO}_2\text{max}$ when subjecting the same individual to 5 Tmax trials (average 17.3%). A similar study by Graham and McLellan (1989) calculated a 10% variability for Tmax tests at 120% $\text{vVO}_2\text{max}$. However, not in accordance to the previous research listed, Billat et al. (1994a) showed no significant difference in Tmax at 100% $\text{vVO}_2\text{max}$ in 8 runners over a one-week period.

Even among athletes with a homogenous $\text{vVO}_2\text{max}$, there is a distinct variability in Tmax. Billat et al. (1996) showed a 25% coefficient of variation in Tmax tests, with the average lasting about 6 minutes at $\text{vVO}_2\text{max}$. A 1994 study displayed a negative correlation of Tmax and $\text{vVO}_2\text{max}$ (Billat, Renoux, Pinoteau, Petit, & Koralsztein, 1994b). This study was supported by James and Doust in 1999 who investigated the effects of prior intense exercise on Tmax. Tmax has also been shown to be negatively correlated to $\text{vVO}_2\text{max}$ (Billat, Renoux, et al., 1994b; Billat, Renoux, Pinoteau, Petit, & Koralsztein, 1995), meaning high performing endurance athletes will likely have a smaller Tmax than their low performing counterparts at the same percentage of their respective $\text{vVO}_2\text{max}$. However, there exists a positive correlation between Tmax and anaerobic threshold (Billat, Renoux, et al., 1994b; Hill & Rowell, 1996). Hill and Rowell (1996) believed that Tmax and $\text{vVO}_2\text{max}$ alone were not enough to sufficient for prescribing intervals since anaerobic threshold accounted for 44% of the variability in Tmax. In fact, an athlete’s anaerobic capacity may be linked to the variability in Tmax. There is a positive correlation between Tmax at 100% $\text{vVO}_2\text{max}$ and 120% $\text{vVO}_2\text{max}$
(Renoux, Petit, Billat, & Koralsztein, 2000). Since Tmax at 120% vVO$_2$max is a measure of anaerobic capacity (Scott, Roby, Lothman, & Bunt, 1991), Tmax could be correlated to an athlete’s ability to anaerobically produce energy.

**Tmax as an interval duration.** To be properly labeled as a VO$_2$max interval, VO$_2$max should be met during the duration of the exercise. Due to the large variability in Tmax, it has been suggested that interval durations of 50-70% of Tmax be used for VO$_2$max intervals rather than fixed durations (Billat, 2001; Laursen & Jenkins, 2002; Laursen, Shing, & Jenkins, 2004; Smith et al., 2003; Smith et al., 1999). Hill and Rowell (1996) noted that if the goal of an exercise was to reach VO$_2$max during the first interval in a sequence of intervals at vVO$_2$max, a duration of no less than 60% of Tmax was required. Several studies have shown that at this intensity, VO$_2$max is reached on average at 60% Tmax (Billat, Petit, & Koralsztein, 1996; Esfarjani & Laursen, 2007; Hill & Rowell, 1996; Smith et al., 1999). Most of these studies have focused on runners, but in 2004 Laursen et al. demonstrated that on average, 74% of Tmax was required for a group of highly trained cyclists to reach VO$_2$max. Peiffer et al. (2005) believed that this was possibly due to an inflated pVO$_2$max value from a GXT with 30-second stage protocols. They used both a 1-minute and a 3-minute stage GXT to determine pVO$_2$max in trained cyclists and elicited VO$_2$max at nearly 60% Tmax for both protocols (61.8 ± 7.00 and 62.10 ± 10.5%). From this, we can assume that a duration of 60% Tmax is appropriate for eliciting VO$_2$max in both runners and cyclists. In addition, as reported earlier, intervals at 60% Tmax have proven beneficial in improving 40km TT performance compared to intervals at 30-second intervals at 175% pVO$_2$max.
While it’s been determined that VO$_2$max is elicited on average at 60% Tmax for exercise at vVO$_2$max, VO$_2$max is often maintained for several minutes after it is initially elicited (Billat et al., 1996). This allows for the possibility of an increased exercise duration while still eliciting VO$_2$max. However, Smith et al. (2003) compared 4-week interval training programs with interval durations of 60% and 70% Tmax on 3000m running performance. There was a significant improvement in 3000m running performance in the 60% Tmax group compared to the 70% Tmax group (17.6 ± 3.5s vs. 6.4 ± 4.2s). This was thought to occur due to an extended total time at a high velocity as only 5 intervals were able to be completed per session in the 70% Tmax group compared to 6 intervals in the 60% Tmax group leading to average high velocity times of 655 seconds and 768 seconds respectively. In addition, they believe that increases in performance may have been due to an increased VT of 6.8% in the 60% Tmax group compared to a 1.7% improvement in the 70% Tmax group. From this information, we can hypothesize that an interval duration of 60% Tmax is ideal in improving aerobic performance in cyclists.

**Prior Heavy Exercise**

Prior heavy exercise has the ability to affect a subsequent bout of exercise if recovery is insufficient. Burnley et al. (2006) looked at passive recovery durations of 10, 20, 30, 45, and 60 minutes on two 6-minute bouts of heavy exercise [70% between gas-exchange threshold (GET) and pVO$_2$max]. They determined that a duration of 45 minutes was necessary for VO$_2$ kinetics to return to a normal profile. However, many of the benefits of intervals stem from incomplete recovery and the body’s ability to return to
exercise from a “primed” state. In addition, due to time constraints, workouts are often crammed into short time periods in which long recovery durations are not feasible.

**VO₂ kinetics.** At the onset of heavy exercise, defined as an intensity above the GET, VO₂ is thought to increase in a 3-phase model as defined below (Hughson, O'Leary, Betik, & Hebestreit, 2000):

- **Phase 1:** Lasting ~15 seconds and mainly due to increased venous return
- **Phase 2:** The primary phase due to changes in oxidative metabolism and increased oxygen extraction during exercise
- **Phase 3:** An additional phase due to O₂ demand above the required metabolic work rate. Also known as the VO₂ slow component

The time to reach 63% of the increase in VO₂ above baseline levels (τ) is known as the VO₂ time constant and is a measure of the rate in which VO₂ rises (Carita, Greco, & Denadai, 2014). If between two trials there is a decrease in τ, there is an assumed acceleration of VO₂ kinetics. Prior heavy exercise is thought to alter VO₂ kinetics in a following exercise bout. In 1996, Gerbino, Ward and Whipp examined the effects of both moderate (sub LT) and heavy (supra LT) exercise on a subsequent bout of moderate or heavy exercise. Exercise bouts lasted 6 minutes and were separated by 6 minutes of passive recovery. They reported accelerated VO₂ kinetics during heavy exercise that was preceded by a heavy exercise bout (τ = 56s for passive vs. 37s). However, there was no alteration in VO₂ kinetics on moderate exercise that was preceded by a heavy exercise. A similar study by Burnley et al. (2001) looked at cyclists exercising for 6 minutes at a moderate intensity (80% LT) or a heavy intensity (50% between LT and pVO₂max)
followed by 6 minutes of 20W pedaling. This was followed by a subsequent bout of 6 minutes of moderate or heavy exercise. They found that while there was an increase in baseline VO$_2$, VO$_2$ kinetics were unchanged if moderate cycling was performed prior to or post an exercise bout. This agreed with the work performed by Gerbino et al. (1996), but also allowed the cyclists to cycle during the recovery periods as would be seen during a field workout. They too found acceleration in VO$_2$ kinetics in a bout of heavy exercise that was preceded by a heavy bout.

There has been considerable controversy as to whether the increase in end value VO$_2$ following a heavy exercise bout is truly due to an increase in VO$_2$ kinetics, or whether it is simply due to an elevated baseline VO$_2$. A 2009 study looked at 36 minutes of alternating 6-minute bouts of heavy exercise (85% PPO) and moderate exercise (35% PPO) (Faisal, Beavers, Robertson, & Hughson, 2009). They determined that prior heavy exercise led to both a significantly increased baseline VO$_2$ and acceleration in VO$_2$ kinetics in a following heavy exercise bout. They postulated the mechanisms possibly responsible for this response included increasing blood flow to exercising muscles from increased accumulation of vasoactive metabolites and a right shift of the oxy-hemoglobin dissociation curve due to increasing body acidity and temperature.

The acceleration in VO$_2$ kinetics found by Faisal et al. (2009) is in direct contrast to studies by Burnley and colleagues (Burnley, Doust, Ball, & Jones, 2002; Burnley et al., 2001). They found no acceleration in VO$_2$ kinetics when a heavy exercise bout was preceded by heavy exercise bout, and believed that the overall acceleration toward VO$_2$max was due to an increased amplitude of Phase II and a decreased amplitude of
Phase III VO₂ kinetics. They believed that Phase II lasted longer (3.6% increase) due to increased muscle unit recruitment, and this prolonging of Phase II is what leads to a decrease in the time required to reach VO₂max rather than an acceleration in VO₂ kinetics.

**Rationale**

It is evident that interval training is an effective training method in cycling and is beneficial in increasing performance compared to continuous exercise for both trained and untrained cyclists. A common interval training type in cycling is known as “VO₂max intervals”, which is thought to increase endurance based performance in both runners (3000/5000m) and cyclists (40km) (Laursen et al., 2002; Smith et al., 1999).

Several studies have determined the validity of using pVO₂max as an interval duration to increase endurance performance. Although there has been some disagreement, most studies have shown that VO₂max is elicited at 60% of Tmax at 100% pVO₂max. The use of using a percentage of an individual’s Tmax as an interval duration is a novel concept as there is substantial variability in Tmax among individuals. Consequently, the use of 60% Tmax as an interval duration has been studied extensively. Smith et al. (2003) resolved that 60% Tmax intervals were beneficial in increasing 3000m running performance compared to 70% Tmax intervals. Similarly, Laursen et al. (2002) showed a significant increase in 40km TT performance in cyclists using 60% Tmax intervals compared to 12 x 30sec intervals at 175% PPO. From these studies, we can hypothesize that the optimal VO₂max interval session is one that allows an athlete to minimally elicit VO₂max (60% Tmax), and then allows for immediate recovery.
What becomes less clear is how the time to reach VO$_2$max is altered during successive VO$_2$max intervals. If the goal in optimizing VO$_2$max intervals is to minimally elicit VO$_2$max, then immediately recover; will this alter the duration of each successive interval? Burnely et al. (2002) and Faisal et al. (2009) have already documented a change in VO$_2$ kinetics during an interval following a prior heavy exercise bout. However, these studies were conducted at an intensity below pVO$_2$max and only looked at the effect of a single exercise bout on a following one. There remains a gap in the literature on studies involving subsequent intervals at pVO$_2$max and how this affects the time to reach VO$_2$max.
Participants

Twelve trained, competitive male cyclists volunteered for this study. Subjects were recruited through social media and word of mouth. The subjects had the following characteristics: [29.7 (5.6) years, 184.5 (4.4) cm, 77.6 (7.2) kg, and 67.8 (4.1) VO$_2$max (ml/kg/min$^{-1}$)]. Subjects had been training for endurance cycling competition for at least 2 years (≥5 hours/week), race competitively (≥5x/year) and were familiar with high-intensity interval training. All subjects were determined as low health risk (ACSM, 2013). Participants were asked to refrain from engaging in high-intensity exercise for 48 hours prior to any of the tests.

Diet and Training Log

Participants were asked not to consume excessive amounts of alcohol, caffeine, food or water in the 4 hours prior to the test and to eat their typical pre-race meal 2-3 hours prior to testing. Participants were asked to fill out a 7-day training log prior to the first test and to repeat that exact training between testing days. The University Internal Review Board for the Protection of Human Subjects approved the procedures and health questionnaire and consent forms before trials began (Appendices A and B). Participants were made aware of their commitments, benefits, and risks to the test prior to any testing. Consent forms, health questionnaires, and training logs were also collected prior to the start of testing. To ensure anonymity, all participants were assigned a coded subject number that is not identified in the results section.
Experimental Design

Participants reported to the lab on two different occasions, equating to a total laboratory commitment time of approximately four hours. During the first visit, anthropometric measurements of height and weight were collected for each participant. Participants then completed a GXT to determine VO$_2$max. Following 30 minutes of rest, participants then completed a time to fatigue test at their pVO$_2$max. Participants were then asked to return 7 days later to perform an interval training program. All tests took place in a thermostatically controlled building on campus.

Graded exercise test. All tests were conducted on a Lode cycle ergometer (Gronigen, Netherlands). The saddle and handlebars were adjusted to mimic the cyclist’s natural position according to their own road bike. Participants were encouraged to bring in their own pedals and cycling shoes. Participants were allowed to warm-up at their own cadence and wattage for 15 minutes. During the tests, participants were able to self-select their own cadence in a range of 80-100rpm. Heart rate was collected via telemetry (Polar, Lake Success, New York) and was recorded every 20 seconds. Expired air was continuously analyzed by a computerized metabolic cart (ParvoMedics Trueone 2400, Sandy, Utah) for gas concentrations and volume, and recorded every 20 seconds. A one-way valve and mouthpiece, with headgear to hold the mouthpiece, and a nose clip were placed on the participant and connected to a pneumotach via a large-bore flexible plastic breathing hose.

Expired volume was measured through a heated pneumotach, which was calibrated prior to each participant visit across a variety of flow rates (50–80, 100–200,
200–300, 300–400, & > 400 L/min) using a 3-liter calibrated syringe (Hans Rudolph Inc.). The pneumotach calibration procedure was consistent with manufacturer specifications. The metabolic cart gas analyzers were also calibrated prior to testing using a medically certified gas of known concentration (16% O₂; 4% CO₂).

Initial power was set at 70W and was increased by 35W per minute. The test was terminated when the participant dropped below 60 RPM’s or reached volitional fatigue. pVO₂ max was taken as the power that minimally elicited VO₂ max and determined from the following equation:

\[ pVO_{2max} = (W_{prior} + %W_{end}) \]

where \( W_{prior} \) equals the wattage of the prior 1 minute stage and \( %W_{end} \) equals the fractional time of the terminal stage multiplied by stage wattage increase. The minimal point at which VO₂ max was elicited was determined by the first point in which there was a change of less than 2 mL/kg/min in O₂ consumption with an accompanying heart rate above 90% age-predicted max and a respiratory exchange ratio (RER) above 1.1.

**Time to exhaustion at pVO₂ max.** pVO₂ max was calculated from the GXT as the minimal wattage needed to elicit VO₂ max. After a 5 minute warm-up at a self selected wattage and cadence, the wattage was increased over the course of 20 seconds (16.67% of pVO₂ max every 4 seconds) to pVO₂ max using a computed control to automate the increases. The wattage increase was determined by the following equation:

\[ W_{increase} = pVO_{2max}/6 \]

Participants were blind to the time elapsed and verbally encouraged to ride until fatigue; the test was stopped when the participant’s cadence fell below 60 rpm or reached
volitional fatigue. Expired air was collected and analyzed during the whole trial in the same method as the GXT. Tmax was recorded as time to termination.

**High-intensity intervals.** A standardized 15-minute warm-up protocol was used for each participant prior to the trial (5 min at 20% pVO\(_2\)max, 5 min at 35% pVO\(_2\)max and 5 min at 50% pVO\(_2\)max). Expired air was collected and analyzed throughout the whole trial as outlined in GXT methods. Participants completed an interval-training program consisting of alternating bouts of high-intensity exercise (pVO\(_2\)max) followed by active recovery (20W). The duration of the high-intensity intervals corresponded to 60% Tmax and there was a 1:1 work to recovery ratio. When switching from active recovery to pVO\(_2\)max, the wattage was increased over the course of 20 seconds (16.67% pVO\(_2\)max every 4 seconds) to standardize the recovery period with previous studies (Burnley et al., 2002; Burnley et al., 2001). Participants were asked to complete 5 intervals or to continue to exhaustion, whichever occurred first.

**Data Analysis And Statistics**

Data reported as means ± SD. Participants who were unable to complete the fifth interval set (n=4) were pairwise deleted from statistical analysis of the interval trials. A paired t-test was used to make comparisons of peak values from the GXT and interval trials. A one-way repeated-measures ANOVA was used to detect significant differences in time to reach VO\(_2\)max, and peak values of VO2, RER, VE, and HR for each interval. When significant F-ratios were observed, the *Tukey post hoc* test was used for comparisons (StatSoft Inc, Tulsa, OK). Significance was determined with an alpha level of p<0.05.
Chapter 4

RESULTS

All peak values and relative RCP values from the GXT, as well average Tmax from the time to fatigue test, are listed in Table 2.

<table>
<thead>
<tr>
<th>GXT Variable</th>
<th>Values</th>
<th>% of Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO$_{2\text{peak}}$ (ml/kg/min$^{-1}$)</td>
<td>67.8 (4.1)</td>
<td></td>
</tr>
<tr>
<td>pVO$_{2\text{max}}$ (watts)</td>
<td>391.5 (21.2)</td>
<td></td>
</tr>
<tr>
<td>HR$_{\text{peak}}$ (bpm)</td>
<td>180.7 (11.5)</td>
<td></td>
</tr>
<tr>
<td>VE$_{\text{peak}}$ (L/min)</td>
<td>168.7 (24.9)</td>
<td></td>
</tr>
<tr>
<td>W$_{\text{peak}}$ (watts)</td>
<td>432.5 (20.9)</td>
<td></td>
</tr>
<tr>
<td>Tmax (min)</td>
<td>4.3 (2.1)</td>
<td></td>
</tr>
<tr>
<td>VO$_{2\text{RCP}}$</td>
<td>61.7 (3.9)</td>
<td>91%</td>
</tr>
<tr>
<td>HR$_{\text{RCP}}$</td>
<td>165.7 (10.3)</td>
<td>92%</td>
</tr>
<tr>
<td>W$_{\text{RCP}}$</td>
<td>367.2 (19.8)</td>
<td>85%</td>
</tr>
</tbody>
</table>
Comparison of GXT to Intervals

Peak values of VO\(_2\), HR, and VE for the GXT and interval trials are listed in Table 3. There was a significant difference (p<0.05) in peak values of VO\(_2\) and VE in the interval trials compared to the GXT, leading to a 3.9% and 8.6% increase respectively. There was a trend observed in HR (p=0.08) in HR from the GXT to the intervals.

Table 3. Comparison of peak values from GXT and Intervals

<table>
<thead>
<tr>
<th></th>
<th>Peak Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GXT</td>
</tr>
<tr>
<td>Peak VO(_2) (mL/kg/min(^{-1}))</td>
<td>67.8 (4.1)</td>
</tr>
<tr>
<td>Peak HR (bpm)</td>
<td>180.7 (11.5)</td>
</tr>
<tr>
<td>Peak VE (L/min)</td>
<td>168.7 (24.9)</td>
</tr>
</tbody>
</table>

(*) Significantly different (p<0.05) from GXT

RER. Peak RER values occurred during the recovery periods of the interval trials. Expired air was not collected after the 5\(^{th}\) interval, and thus only 4 peak values for RER were used for statistical analysis. A comparison of peak RER values for the GXT and each interval showed significant differences (F=11.41, p<0.05) and is graphically represented in Figure 1. There was a significant difference in peak RER in intervals 1, 2, and 3 compared to the GXT. There was no significant difference between peak RER achieved during interval 4 and the GXT.
Peak RER values showed significant differences over the course of the intervals (F=13.39, p<0.05). There was statistical significant difference only between intervals 1 and 4. This is graphically represented in Figure 1. Intervals 2, 3, and 4 were not significantly different from each other. There was a 13.8% decrease in peak RER from Interval 1 to Interval 4.

Figure 1. Peak RER presented for GXT and intervals
(*) Significantly different (p<0.05) from the GXT.
(‡) Significantly different from interval 4.
Interval Trials

Means values for time to reach VO₂max, and peak VO₂, VE, HR, and RER for each interval are listed in Table 4. Peak RER values occurred during the recovery periods of the interval trials. Expired air was not collected after the 5th interval, and thus only 4 peak values for RER were used for statistical analysis. All variables showed significant differences from interval 1.

Table 4. Means values from interval trials.

<table>
<thead>
<tr>
<th>Mean Values</th>
<th>Interval 1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to reach VO₂max (%Tmax)</td>
<td>63.77* (13.61)</td>
<td>47.06* (8.91)</td>
<td>38.75 (8.04)</td>
<td>37.10 (6.27)</td>
<td>32.97 (10.53)</td>
</tr>
<tr>
<td>Peak VO₂ (mL/kg/min⁻¹)</td>
<td>63.2* (4.3)</td>
<td>67.5* (3.7)</td>
<td>69.3 (3.5)</td>
<td>70.2 (3.5)</td>
<td>71.2 (3.7)</td>
</tr>
<tr>
<td>Peak VE (L/min)</td>
<td>144.6* (16.6)</td>
<td>154.9* (24.0)</td>
<td>164.6* (25.8)</td>
<td>172.3 (26.2)</td>
<td>181.1 (23.0)</td>
</tr>
<tr>
<td>Peak HR (bpm)</td>
<td>171.4* (10.9)</td>
<td>177.3* (8.9)</td>
<td>180.6* (8.9)</td>
<td>182.5 (8.1)</td>
<td>183.7 (9.3)</td>
</tr>
<tr>
<td>Peak RER (VCO₂/VO₂)</td>
<td>1.45* (0.2)</td>
<td>1.34 (0.2)</td>
<td>1.29 (0.2)</td>
<td>1.25 (0.1)</td>
<td></td>
</tr>
</tbody>
</table>

(*) Significantly different (p<0.05) from last interval.

All values were significantly different (p<0.05) from Interval 1.
Time to reach VO\textsubscript{2}max and RER. Figure 2 shows VO\textsubscript{2} and RER values over the course of the intervals. A 9-point moving average was used to smooth the data. Note that in each subsequent interval, subjects appear to spend an increased time at a VO\textsubscript{2} greater than the peak VO\textsubscript{2} achieved during the GXT. Also note that RER values peak during the recovery period of the intervals and peak RER’s decrease with each subsequent intervals.

Figure 2. VO\textsubscript{2} and RER values presented over the course of the interval trials
**Time to reach VO\textsubscript{2max}**. Time to reach VO\textsubscript{2max} showed significant differences (F=16.5, p<0.05) over the course of the intervals. Time to reach VO\textsubscript{2max} was significantly different in intervals 1 and 2 compared to Interval 5. This is graphically represented in Figure 3. Intervals 3, 4, and 5 were not significantly different from each other. There was a 48.3% decrease in time to reach VO\textsubscript{2max} from Interval 1 to Interval 5. Mean values can be seen in Table 4

![Figure 3](image-url)

*Figure 3. Time to reach VO\textsubscript{2max} presented for each interval

(*) Significant difference (p<0.05) compared to interval 5.*
Peak VO₂. Peak VO₂ showed significant differences over the course of the intervals (F=30.74, p<0.05). Statistical significant difference was found in intervals 1 and 2 compared to Interval 5. This is graphically represented in Figure 4. Intervals 3, 4, and 5 were not significantly different from each other. There was a 12.7% increase in peak VO₂ from Interval 1 to Interval 5. Mean values can be seen in Table 4.

![Figure 4. Peak VO₂ presented for each interval](image)

(*) Significant difference (p<0.05) compared to interval 5
**Peak VE.** Peak VE showed significant differences over the course of the intervals (F=32.35, p<0.05). Intervals 1, 2, and 3 were significantly different from interval 5. This is graphically represented in Figure 5. Intervals 4 and 5 were not significantly different from each other. There was a 25.2% increase in VE over the course of the intervals. Mean values can be seen in Table 4.

![Figure 5. Peak VE presented for each interval (* Significant difference (p<0.05) compared to interval 5)](image-url)
**Peak HR.** Peak HR showed significant differences over the course of the intervals (F=49.68, p<0.05). Intervals 1, 2 and 3 were significantly different from interval 5. This is graphically represented in Figure 6. Intervals 4 and 5 were not significantly different from each other. There was a 7.2% increase in HR over the course of the intervals. Mean values can be seen in Table 4.

![Figure 6. Peak HR presented for each interval](image)

(*) Significant difference (p<0.05) compared to interval 5
The results of this study support the idea of accelerated VO$_2$ kinetics in a heavy exercise bout that is preceded by a similar heavy exercise bout as described in previous studies (Burnley et al., 2011; Gerbino et al., 1996; M. Macdonald, Pedersen, & Hughson, 1997).

**Tmax**

VO$_2$max was achieved at 63.8 (13.6)% of the time to fatigue test. This is very similar to the 60% value that has been reported in several studies (Billat, 2001; Esfarjani & Laursen, 2007; Hill & Rowell, 1996; Peiffer et al., 2005; Smith et al., 1999). This data conflicts with the 74% value attained in 2004 by Laursen et al., but this is believed to be due to a short stage GXT protocol that inflated pVO$_2$max. The 63.8% time to reach VO$_2$max is a confirmation of our hypothesis.

**Time to Reach VO$_2$max**

There was a significant decrease in the time to reach VO$_2$max over the duration of the interval trials, as seen in Table 4, however once subjects completed the 3rd interval, there were no significant changes seen in subsequent intervals. Since significant changes were not seen in all 5 intervals, we reject our original hypothesis. Several different mechanisms have been proposed for this change in VO$_2$ kinetics during subsequent high-intensity exercise bouts.

**Mechanisms.** One seemingly simple explanation for the decrease in time to reach VO$_2$max is that VO$_2$max is still being achieved at 60% of Tmax, but Tmax is decreasing
over the duration of the intervals. Four subjects were unable to complete the 5th interval set, indicating that this interval duration was probably close to Tmax on average for all subjects. If this is true, then VO2 max was achieved at 55% of the new Tmax during the last interval, a value similar to 60%. This theory is supported by a similar study by James and Doust in 2000. They reported a 24% decrease in Tmax following six 800m running interval bouts at 1km/h below vVO2 max. However, other studies have also shown changes in VO2 kinetics following a single priming exercise with no subsequent change in Tmax (Burnley et al., 2001; Carter et al., 2005). It is possible that the decrease in the time to reach VO2 max is due to a combination of these factors, with priming exercise affecting the early intervals and changes in fatigue and Tmax affecting the latter.

There is also reason to believe that the decrease in time to reach VO2 is due to improved O2 delivery to the muscles. Faisal et al. (2009) saw an acceleration in Phase II VO2 kinetics (τ reduced from 27.4s to 23.8s) in heavy exercise (6 min ay 85% VO2 peak) that was preceded by heavy exercise without a change in cardiac (Q) kinetics. They concluded that the change in VO2 kinetics during heavy exercise is function of improved O2 diffusion.

Our study appears to support their conclusion. We saw a significant increase in VE and HR in the first 3 intervals. This suggests an increase in the O2 delivery to the working muscles to produce ATP. ATP hydrolysis is responsible for increases in H+ ion concentration (Robergs, Ghiasvand, & Parker, 2000). Increased H+ ion concentration leads to a decrease in blood pH. Decreased pH causes hemoglobin to lose its affinity for oxygen and causes a rightward shift in the oxyhemoglobin dissociation curve, thus
increasing O₂ unloading to the muscle. This could be a reason for the acceleration in VO₂ kinetics and a decreased time to reach VO₂ max. In addition, further studies have reported increases in H⁺ concentration and muscle temperature, which also increases O₂ unloading to the muscle. Heavy priming exercise could also result in increased heat production (Krustrup, González-Alonso, Quistorff, & Bangsbo, 2001; M. J. MacDonald, Naylor, Tschakovsky, & Hughson, 2001).

Changes in muscle activity are another possible cause for alterations in VO₂ kinetics in successive exercise bouts. Muscular fatigue has been associated with increases in H⁺ ion concentrations, which can causes decreases in the sensitivity of muscle tension development during exercise (Metzger & Moss, 1987). As muscle fatigue increases, the fibers are no longer able to produce the tension required to produce the same power output, and thus additional recruitment of muscle fibers are recruited (Burnley et al., 2002). This leads to a greater O₂ cost of exercise (Hughson et al., 2000). We previously suggested fatigue as a mechanism for decreasing Tmax in the latter intervals. The significant increase in VE we reported is also likely due to increased O₂ demand from additionally recruited muscle fibers (Noakes & Marino, 2009).

It appears that the decrease in time to reach VO₂ max during subsequent high-intensity intervals is due to a combination of several factors rather than a single cause. Significant increases in VE and HR support the roles of increased fatigue, H⁺ ion concentration, and the recruitment of additional motor units, in altering VO₂ kinetics. However, this study found a no significant increase in the time to reach VO₂ max in the
3rd interval with concurrent increases in VE and HR. This suggests there is a limit at which no additional O₂ diffusion can take place despite increases in O₂ supply.

**Exercise Prescription**

The implications of this study are important for the prescription of VO₂max type interval training in athletes. Smith et al. (2003) compared a 4-week interval training program with interval durations of 60% and 70% on 3000m running performance. There was a significant increase in performance in the 60% group compared to the 70% group. The 60% group was able to complete more intervals than the 70% group (6 vs. 5) and thus spend more time at a higher velocity. It can also be presumed that because of the shorter interval duration, subjects spent less time at their VO₂max during their first 5 intervals in the 60% group compared to the 70% group. Results from this study appear to suggest that interval training is beneficial when VO₂max is reached while still minimizing the time spent at VO₂max and maximizing the time spent at a high velocity. The results from our study suggest then that subsequent intervals should decrease in duration as VO₂max is being reached sooner (see Table 4). This should also allow for an increased number of intervals completed before exhaustion, thus maximizing the time spent at a high power output. A training intervention is needed however to compare the performance benefits of intervals lasting 60% Tmax to intervals that subsequently decrease in duration so that VO₂max is minimally reached with each interval.

**Peak VO₂, HR, and VE.** What the data from this study does show is that a minimum of the 4 intervals at this duration and intensity are need to maximally stress the cardio-respiratory system. As seen in Figure 3, once subjects got to interval 3, there were
no significant changes seen in further intervals for peak VO$_2$. Similarly, as seen in Figures 4 and 5, there were no significant changes after in HR and VE after interval 4. This suggests that to maximally stress the cardiorespiratory system, at least 4 intervals are required. This refutes our hypothesis that peak VO$_2$, HR, and VE would not be significantly different between intervals.

**RER**

An unexpected response from this study was the decrease in peak RER during the recovery period for each interval. As seen in Figure 1, peak RER was significantly higher during the first 3 intervals than during the GXT. For RER to peak during the recovery period is not uncommon as shown by a singly high-intensity exercise study done by Short and Sedlock in 1997. They saw a brief increase in RER immediately following the cessation of exercise. Post intensive exercise, a subject will hyperventilate as the O$_2$ cost of the working muscle declines, while the drive to restore the acid-base balance through CO$_2$ elimination remains high (Bahr & Sejersted, 1991). What was unexpected however was the drop in RER from the first interval to the subsequent intervals. This would however offer an explanation as to the decrease in time to reach VO$_2$ max. The role of hyperventilation is to maintain the body’s acid-base balance through the exhalation of excess CO$_2$, thus decreasing acidity. The significant decrease in RER seen over the duration of the intervals suggests a decrease in acid buffering. This would cause subsequent interval to begin at a lower pH, thus causing increased O$_2$ unloading to the muscle as described earlier.
GXT vs. Intervals

A final controversial finding of this study was the significant increase in peak VO₂ and VE in the interval trials compared to the GXT values as seen in Table 3. GXT’s have long been considered the golden standard for VO₂max testing. However, several intermittent and discontinuous tests have been shown to elicit a significantly higher VO₂ max than conventional GXTs (Edwards, DeBenedictis, Lowder, & Evans, 1999; Mauger & Sculthorpe, 2012; Mier & Alexander, 2011). Beltrami et al. (2012) saw an increase of 4% in VO₂max using a decremental protocol that involved the subject starting a high workload and slowly decrease in intensity. This is similar to the 3.9% increase that was found in our study.

There are two prevailing theoretical models that explain the mechanisms that limit VO₂max. The first is that the heart reaches a maximal capacity to provide O₂ to the working muscles (Smirmaul, Bertucci, & Teixeira, 2013). The second is the cardiovascular system never reaches a maximum, and that VO₂max is limited by the number of motor units that can be recruited (T. D Noakes & Marino, 2009). The results of our study appear to support the latter theory. There was no significant increase in peak VO₂ during the 3rd interval despite a significant increase in HR and VE. This suggests that O₂ supply may not be a limiting factor of VO₂max, but motor unit recruitment may not be maximized during the GXT.

One possible reason for the significant increase in VO₂max may have been due to the active recovery periods. Active recovery is associated with increased lactate clearance and increased blood flow and oxygen delivery to the active muscles (Bangsbo, Graham,
Increased blood flow also improves phosphocreatine re-synthesis, which is dependent on aerobic metabolism (Bogdanis, Nevill, Boobis, & Lakomy, 1996). This may increase the force production of the muscle that is a possible limitation of end stage exercise during a GXT rather than oxygen delivery. This would allow for VO$_2$ kinetics to continue to rise rather than plateau due to muscular fatigue.

**Implications of findings.** While the possibility of achieving a higher VO$_2$max with a non-continuous testing protocol appears on the surface to have great implications in the prescription of exercise testing, that may not necessarily be so. VO$_2$max is greatly over-used in the athletic community as a marker for athletic performance. We have already discussed how pVO$_2$max is a great predictor of athletic performance. VO$_2$max is also unusable in the prescription of exercise intensity and duration. If one simply wants to know their VO$_2$max, a non-continuous test may be the most beneficial, but GXT’s that allow for the determination of ventilatory thresholds and powers at different intensities are the most beneficial for exercise prescription and the prediction of athletic performance.

**Conclusion**

The findings from our study support the theory that VO$_2$ kinetics in a heavy exercise bout are altered to allow VO$_2$max to be reached sooner when that exercise is preceded by another heavy exercise bout. In addition, our data supports the idea that VO$_2$ kinetics will continue to be altered in a further subsequent bout, but will reach a point where additional bouts have no affect on the time to reach VO$_2$max. Our study also
supports the theory that peak VO$_2$ and the time to reach VO$_2$ max is limited by O$_2$

extraction rather than O$_2$ supply.

This has great implications on the duration and number of intervals needed to
maximally stress the cardio-respiratory system during VO$_2$ max type intervals. It appears
that subsequent intervals should decrease in duration, and that at least 4 intervals are
needed to produce maximal levels of cardio-respiratory stress, but further training
interventions studies are need to prove the efficacy of this statement.
APPENDIX A

HEALTH HISTORY AND TRAINING QUESTIONNAIRE

SUBJECT ID: __________________________
GENDER: ____________ AGE _______ yrs

| WEIGHT _______ lbs | HEIGHT _______ in | BP _______/____ mmHg | This box is for personnel only |
|-------------------|-------------------|------------------------|
| HR _______ beats/min | BMI __________ |                        |

Medical History

Do you have a history of high blood pressure? YES NO

Have you or do you currently smoke? YES NO
If YES, when did you quit: ______________________

Have you ever had your cholesterol measured? YES NO
If yes, please answer the following
Total Cholesterol _______________
HDL _______________
LDL _______________

Are you diabetic or have any signs of diabetes such as frequent urination or extreme thirst: YES NO

Are you currently taking any medications? YES NO
If you circled YES, please list:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

Please list all Medical Conditions (e.g. musculoskeletal injuries, arthritis, ulcers, mono, hepatitis):
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

Please list any hospitalizations or surgeries and their dates:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
Do you have any physical limitation that might prevent you from being in this study (e.g. back, knee, ankle pain or any other injury that limits your movement on a bicycle)? If so, please list:
________________________________________________________________________
________________________________________________________________________

Family History:
Have you had any immediate family members (parents, siblings, offspring) with a current or previous heart condition (heart attack, chest pain etc.)? If so, please list and age occurred.
________________________________________________________________________
________________________________________________________________________

Have you ever experienced any of the following:

<table>
<thead>
<tr>
<th>Condition</th>
<th>YES</th>
<th>NO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain in the neck, chest, or jaw</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shortness of breath w/mild exertion</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Dizziness or passing out</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Rapid breathing at night</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Swollen Ankles</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Abnormal heart beat</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Calf pain with exercise</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Known heart murmur</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Unusual fatigue or shortness of breath</td>
<td>YES</td>
<td>NO</td>
</tr>
</tbody>
</table>

Training Status

How long have you been training for (months/years)? ______________________

On average, how many hours do you train per week? ________________________

Do you race bicycles competitively? YES NO
If YES, what category are you? ______________
If YES, how many times per year? _____________

Do you regularly train using high-intensity intervals? YES NO
If YES, how often? ________________________

Please fill out the forms of the following 2 pages.
AHA/ACSM Health/Fitness Facility Preparticipation Screening Questionnaire*
(Medical History Form)

Assess your health status by marking all true statements

<table>
<thead>
<tr>
<th>History</th>
<th>Other Health Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>You have had:</td>
<td>__ You have diabetes.</td>
</tr>
<tr>
<td>_ a heart attack</td>
<td>__ You have a heart attack</td>
</tr>
<tr>
<td>_ heart surgery</td>
<td>__ You have asthma or other lung disease.</td>
</tr>
<tr>
<td>_ cardiac catheterization</td>
<td>__ You have burning or cramping sensation in your lower legs when walking short distances</td>
</tr>
<tr>
<td>_ coronary angioplasty (PTCA)</td>
<td>__ You have musculoskeletal problems that limit your physical activity</td>
</tr>
<tr>
<td>_ pacemaker/implantable cardiac defibrillator, or rhythm disturbance</td>
<td>__ You have concerns about the safety of exercise.</td>
</tr>
<tr>
<td></td>
<td>__ You take prescription medication(s).</td>
</tr>
<tr>
<td></td>
<td>__ You are pregnant.</td>
</tr>
<tr>
<td>_ heart valve disease</td>
<td></td>
</tr>
<tr>
<td>_ heart failure</td>
<td></td>
</tr>
<tr>
<td>_ heart transplantation</td>
<td></td>
</tr>
<tr>
<td>_ congenital heart disease</td>
<td></td>
</tr>
<tr>
<td></td>
<td>If you marked any of these statements in this section, consult your physician or other appropriate health care provider before engaging in exercise. You may need to use a facility with a medically qualified staff.</td>
</tr>
</tbody>
</table>

Symptoms

You experience chest discomfort with exertion. You experience unreasonable breathlessness. You experience dizziness, fainting, or blackouts. You take heart medications.

Other Health Issues

If you marked any of these statements in this section, consult your physician or other appropriate health care provider before engaging in exercise. You might benefit from using a facility with a professionally qualified exercise staff to guide your exercise program.

Cardiovascular Risk Factors

If you marked two or more of the statements in this section you should consult your physician or other appropriate health care provider before engaging in exercise. You might benefit from using a facility with a professionally qualified exercise staff to guide your exercise program.

- You are a man older than 45 years.
- You are a woman older than 55 years, have had a hysterectomy, or are postmenopausal.
- You smoke, or quit smoking within the previous 6 months.
- Your blood pressure is > 140/90 mmHg.
- You do not know your blood pressure.
- You take blood pressure medication.
- Your blood cholesterol level is > 200 mg/dl.
- You do not know your cholesterol level.
- You have a close blood relative who had a heart attack or heart surgery before age 55 (father or brother) or age 65 (mother or sister).
- You are physically inactive (i.e., you get < 30 minutes of physical activity on at least 3 days per week.)
- You are > 20 pounds overweight.

None of the above

You should be able to exercise safely without consulting your physician or other appropriate health care provider in a self-guided program or almost any facility that meets your exercise program needs.


**Professionally qualified exercise staff refers to appropriately trained individuals who possess academic training, practical and clinical knowledge, skills, and abilities commensurate with the credentials defined in Appendix F of the ACSM Guidelines 2006.
Please list your exercise regimen for the past 7 days

<table>
<thead>
<tr>
<th>Training Diary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Day</strong></td>
</tr>
<tr>
<td>Monday</td>
</tr>
<tr>
<td>Tuesday</td>
</tr>
<tr>
<td>Wednesday</td>
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<tr>
<td>Thursday</td>
</tr>
<tr>
<td>Friday</td>
</tr>
<tr>
<td>Saturday</td>
</tr>
<tr>
<td>Sunday</td>
</tr>
</tbody>
</table>
APPENDIX B

INFORMED CONSENT

Changes in Time to Reach VO2max During Intervals at VO2max Power

You are invited to participate in a research study looking at how interval training affects the time required to reach maximal oxygen consumption (VO2max). This study is being conducted by Adam Switters in the Kinesiology department at California State University, Sacramento with laboratory assistance provided by Daryl Parker, PhD, and other graduate students. Total study time commitment will be about 4 hours of laboratory time spread over a week.

Purpose

The purpose of this research is to see if the time to reach VO2max is altered during successive high-intensity intervals. If you decide to participate, you will be asked to visit the laboratory on two separate occasions (one week apart). You will also be asked to fill out a training diary, as listed in the health history and training questionnaire, for the week before the first test, and to replicate that same training in the week between laboratory visits.

Testing Procedures

Maximal Stress Testing: During your first visit, you will be participating in a maximal exercise test on an electronically braked cycle ergometer. The test will start at 70 watts and the wattage will increase 35 watts every minute. The test will terminate when a cadence of 70 rpms can no longer be maintained. You will be breathing through a one-way valve during testing to capture and analyze expired air while wearing supportive headgear and a noseclip.

Constant Load Test to Exhaustion: Following a 30 minute rest for recovery and water, you will be participating in a constant load test to exhaustion on the cycle ergometer. The wattage will be set at the minimal power associated with your maximal oxygen consumption (pVO2max) from your first test. You will be asked to maintain this wattage as long as possible, with the test terminating when you are no longer able to maintain a cadence of 70 rpms.

High-Intensity Intervals: You will be asked to return to the laboratory after one week at approximately the same time (within 2 hours). The last test will involve a series of intervals with alternating bouts of high-intensity work (pVO2max) and low-intensity work (20W). Each interval will last 60% of your time to exhaustion test. You will be asked to complete 5 intervals, or to ride till exhaustion, whichever comes first.
Risks and Discomforts
During exercise testing, you will experience an increase in blood pressure, rapid breathing, sweating, increased exertion, fatigue and muscular discomfort. Exercise testing is associated with a low risk of death (<0.01% and 5x less in females) and heart complications (<0.1%). These risks are even lower for individuals who exercise regularly. If any adverse effects do occur during testing, you will be referred to the your personal physician or the CSUS Student Health Center if you are a current student. In case of any acute symptoms or an emergency, the California State University, Sacramento Emergency Response Manual will be followed. The research participant will be responsible for any medical treatment that may occur. The primary investigator (Adam Switters) is certified in CPR and will be available at all times.

Benefits of the Testing Procedure
You will receive information on your current state of health and fitness. You will receive a copy of your maximal stress test which may be used as a baseline for you to develop a training program to improve your current level of conditioning and for understanding your body’s response to exercise.

Participant Responsibilities
Knowledge of your health status and any abnormalities associated with your health could drastically change the test and affect your safety. It is your responsibility to completely and fully disseminate information regarding your health and condition prior to exercise testing. It is also your responsibility to notify the investigators of any chest pain, chest tightness, indigestion or any other unusual symptoms that occur during testing.

Collection and Protection of Personal Information
The data collected during this study will be treated as confidential. You will be assigned a randomized ID number. All data will be stored using only the randomized ID number and kept in a locked location. All results will be reported as a whole with no identifiable information made public. A master list connecting subject ID number to the subject will be kept in a separate and locked location.

Consent to Participate
Testing is voluntary and you are free to withdraw or not to participate at any time without penalty. You are free to ask questions at any time, including but not limited to clarification on any forms, instructions, or testing procedures that you do not feel comfortable with. If you have questions about the research at any time or if you have a research-related injury, you can reach Adam Switters at (xxx) xxx-xxxx or Dr. Parker at (916) 278-6902. Any questions regarding, problems or concerns with your rights can be directed to research@csus.edu.

Your signature below indicates that you have read and understand the information provided above, that you willingly agree to participate, that you may withdraw your
consent at any time and discontinue participation at any time. Knowing the risks and having had your questions answered to your satisfaction, you hereby consent to participate in this study.

NAME: _______________________________________________________
PHONE: ________________________
EMAIL: ________________________

__________________________________________  ________________
Signature                                      Date
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training using the running speed at maximal O2 uptake and the time for which this


