THE EFFECT OF RUNNING SPEED ON VO₂ KINETICS
IN THE SEVERE EXERCISE DOMAIN

THESIS

Presented to the Graduate Council of the
University of North Texas in Partial
Fulfillment of the Requirements

For the Degree of

MASTER OF SCIENCE

By

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Denton, Texas
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There has been an interest in the kinetics of the VO₂ response during exercise at various intensities. However, most studies focus on the response of submaximal intensities whereas few studies have examined VO₂ kinetics at severe intensities. The purpose of this study was to evaluate the effect of exercise intensity on VO₂ kinetics over a range of severe intensities. Participants were 17 volunteers, both male and female, with a mean VO₂max of 3182 ± 804 ml·min⁻¹. The participants performed an incremental test and five constant power test to fatigue on separate days in the order of 100%, 100%, 110%, 105%, and 95% of the velocity of VO₂max. By the criteria of least-squares error, the data were best-fit by the mono-exponential model with a delay. Consequently, there is no evidence of a slow component at these “severe” intensities suggesting that there may be an upper limit at which there is insufficient time for a slow component to develop.
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In general, VO₂ kinetics can be described as an exponential response which follows a brief delay-like component. Submaximal exercise intensities (40% - 90%) are characterized by "thresholds" which demarcate patterns in the kinetics and confound interpretation of the effect of intensity per se on kinetics. Moderate intensity exercise can be described as exercise below the anaerobic threshold, or exercise during which there is no increase in blood lactate. VO₂ kinetics at intensities below the anaerobic threshold fit a mono-exponential model that results in its steady-state within approximately 3 min in healthy participants. The domain of heavy exercise is described as the intensity above the lactate threshold. The lactate threshold is often referred to as the anaerobic threshold or, when estimated based on ventilatory responses, as the ventilatory (anaerobic) threshold.

At intensities slightly above the lactate threshold the VO₂ kinetics include a slow component which delays the achievement of a stable VO₂. However, given sufficient time VO₂ does stabilize at a submaximal value. At intensities above critical power the slow component drives VO₂ to max. The critical power concept is based on the hyperbolic relationship between power and time to exhaustion. Theoretically, exercise at critical power could be sustained indefinitely.
$V_0_{2\max}$ is the point that oxygen consumption plateaus and shows no further increase as work rate increases. Therefore, to determine $V_0_{2\max}$ an incremental test is administered. There are many protocols for incremental test, however, the speed increases as time increases until the participant cannot continue due to fatigue. Velocity at $V_0_{2\max}$ ($V_{max}$) is also derived from an incremental test. $V_{max}$ is the lowest velocity at which $V_0_{2\max}$ was achieved during this test.

The slow component has been defined as the continued rise in VO$_2$ beyond the third minute of exercise (Barstow, 1994; Casaburi, Storer, Den-Dov, & Wasserman, 1987; Gaesser & Poole, 1996; Gaesser, 1994; Poole et al., 1991; Roston et al., 1987; Whipp, 1994; Whipp & Wasserman, 1986). An additional O$_2$ cost (i.e., slow component) occurs when constant power exercise is performed above the anaerobic threshold. At the onset of exercise above the anaerobic threshold VO$_2$ kinetics respond rapidly and elevate above that predicted from the VO$_2$–work rates relationship at intensities below the anaerobic threshold (Poole, 1994; Henson, 1989; Whipp & Wasserman, 1972; Whipp, 1994). This slow component is separate from the initial exercise response, being initiated following a discrete interval after exercise onset (Barstow & Molé, 1991).

During exercise at intensities below the anaerobic threshold, there is not a slow component, and the VO$_2$ response is described by a monoexponential function where VO$_2$ at any given time ($t$) is

$$V_O_2(t) = V_O_2\text{ baseline} + (V_O_2\text{ final} - V_O_2\text{ baseline}) \cdot (1 - e^{-\frac{t}{\tau}}),$$

with $\tau$ being the time constant of the response. In a given participant, if the delay response (slow component) were linear, the overall response would be described as follows:
\[ \text{VO}_2(t) = \text{VO}_2 \text{ baseline} + [(\text{VO}_2 \text{ final} - \text{VO}_2 \text{ baseline}) \cdot (1 - e^{-t/T})] + \\
(\text{VO}_2 \text{ max} - \text{VO}_2 \text{ SS}) \cdot (S) \]

with \( S \) being the slope of the slow component of the response. However, while attempts have also been made to model the response when there is a slow component, few authors have successfully fit data to a model that includes an initial exponential response followed by a delayed response.

Clearly, there is a slow component to the \( \text{VO}_2 \) response above the lactate or ventilatory threshold. \( \text{VO}_2 \) plateaus only after a two-phase response. At intensities above critical power \( \text{VO}_2 \) achieves \( \text{VO}_2 \text{ max} \) at fatigue. For example, Poole et al. (1991) and Poole, Ward, Gardner, and Whipp (1988) showed that, during exercise at critical power, \( \text{VO}_2 \) reached a steady state at approximately 75\% of \( \text{VO}_2 \text{ max} \) at exhaustion; however, at a power output that was 15 W above critical power, \( \text{VO}_2 \) reached 95 to 97\% of \( \text{VO}_2 \text{ max} \) at exhaustion. This percentage may have been slightly inflated because in three of the eight participants a higher \( \text{VO}_2 \) was elicited in the constant power test (i.e., \( \text{VO}_2 \text{ max} \) was underestimated by the incremental test). Nevertheless, results of these studies suggested that \( \text{VO}_2 \text{ max} \) would not be elicited by exercise at critical power and that it could be elicited by exercise that was at an intensity slightly above critical power, but far from the intensity associated with attainment of \( \text{VO}_2 \text{ max} \) in an incremental test.

**PURPOSE**

Many studies have evaluated \( \text{VO}_2 \) kinetics over a variety of submaximal steady state intensities but few have examined at \( \text{VO}_2 \) kinetics at “max” or “severe” intensities. The purpose of this investigation was to evaluate the effect of exercise intensity on \( \text{VO}_2 \) kinetics
over a range of severe exercise intensities.

The first working hypothesis was that VO₂ kinetics at all intensities (95, 100, 105, and 110% of Vmax) could be described by a monoeponential model and that, only at the lowest intensity (95% of Vmax), the VO₂ kinetics would be described with a two-component model.

The second working hypothesis was that time to VO₂max, and time VO₂max was sustained would be predictably shorter at the faster intensities.

Delimitations
The investigation was delimited in the following ways:

1. Subjects consisted of men and women training 25 or more kilometers per week.
2. Subjects ranged in age from 20 to 32 years.
3. Subjects performed five treadmill tests—one incremental, and five constant power tests.

Limitations
1. Because the investigation is limited to recreational runners, results may not be generalizable to all populations. Furthermore, results may not be generalized to track athletes and athletes from other sports outside of track.
2. Results may not be generalizable to exercise modes beyond those which will be conducted during the investigation.
3. Athletes may not give full effort during all tests. Some cautions must be used in the interpretation of results.
CHAPTER II

REVIEW OF LITERATURE

The purpose of this study was to evaluate the effect of exercise intensity on VO\textsubscript{2} kinetics over a range of high intensities. That is, the purpose was to determine if VO\textsubscript{2} kinetics at high intensities are described by mono-exponential models which result in faster responses than submaximal exercise intensities. In this chapter the results of previous investigations pertaining to oxygen uptake kinetics are discussed.

**Velocity at VO\textsubscript{2}max**

The purpose of the study by Billat, Renoux, Pinoteau, Petit, and Koralsztein (1995) was to examine the relationship between time to exhaustion at 90%, 100%, and 105% of V\textsubscript{max} (the minimum velocity which elicits VO\textsubscript{2}max). The participants were fourteen elite male long-distance runners. An incremental test that began at 12 km·hr\textsuperscript{-1} and was increased by 2 km·hr\textsuperscript{-1} every 3 minutes up to 80% of the runners speed in a 1.5 km race and by 1 km·hr\textsuperscript{-1} thereafter was used to determine VO\textsubscript{2}max, V\textsubscript{max}, and lactate threshold. V\textsubscript{max} was calculated as the slowest incremental stage which elicited a VO\textsubscript{2} value equal to VO\textsubscript{2}max. Finger tip blood samples were taken during the last 30 s of each incremental stage. The test at 90%, 100%, and 105% of V\textsubscript{max} were randomly assigned and separated by a week. These tests began with a 15 minute warmup at 60% of V\textsubscript{max} then 20 s later the speed was
increased and the participant was encouraged to run to exhaustion. The mean \( \text{VO}_2\text{max} \) for these participants was 74.9 ml·kg\(^{-1}\)·min\(^{-1}\) and the mean \( \text{Vmax} \) was 22.4 ± 0.8 km·hr\(^{-1}\).

The study by Hill, Williams, and Burt (1997) had two goals; first to determine if \( \text{Vmax} \) was the lowest intensity that would elicit \( \text{VO}_2\text{max} \), and secondly, to determine how long \( \text{Vmax} \) could be sustained at \( \text{Vmax} \) and at a lower velocity. Participants were six former members of the university men's track team who were specialists in 1500 and 5000 m. \( \text{VO}_2\text{max} \) and \( \text{Vmax} \) were determined from an incremental test starting with three 4-min stages which began at 10.5 km·hr\(^{-1}\) and increased by increments of 1.6 km·hr\(^{-1}\). Participants mean \( \text{VO}_2\text{max} \) was 61.6 ± 9.1 ml·kg\(^{-1}\)·min\(^{-1}\) on the incremental test. Participant performed two other tests at 92% and 100% of \( \text{Vmax} \) on separate days. Tests began with a 4-min warmup at 11.3 km·hr\(^{-1}\) followed by a 5 minute rest and then a run to exhaustion at one of the two velocities. Time to exhaustion was recorded at 92% and 100% of \( \text{Vmax} \). Hill et al. (1997) reported mean \( \text{Vmax} \) as 16.3 ± 1.1 km·hr\(^{-1}\). At exhaustion values for \( \text{VO}_2\text{max} \) and \( \text{V}_E\text{max} \) did not differ from 92% and 100% of \( \text{Vmax} \). Therefore \( \text{VO}_2\text{max} \) was attained at 92% of \( \text{Vmax} \). Time to exhaustion at 92% of \( \text{Vmax} \) was 621 ± 184 s and 100% of \( \text{Vmax} \) was 330 ± 85 s. \( \text{VO}_2\text{max} \) was sustained for a relatively short (32 s) and highly variable (6 to 109 s; \( CV = 128\% \)) period of time at 100% of \( \text{Vmax} \). However, at 92% it took longer to reach \( \text{VO}_2\text{max} \), but it was sustained for a longer (130 s) and less variable (63 to 215 s; \( CV 51\% \)) period of time.

\( \text{VO}_2 \) kinetics

Slow component \( \text{VO}_2 \) versus \( \text{VO}_2 \) predicted from work rates below lactate threshold

Barstow and Molé (1991) and Patterson and Whipp (1991) reported that 80 to 110
s after the onset of exercise, the slow component of VO₂ becomes superimposed upon the rapid initial increase associated with exercise onset. However, the slow component appears to develop more rapidly early in the exercise bout (i.e. minutes 3 to 10) (Gaesser & Poole 1996).

Åstrand and Saltin (1961) performed a study using five participants, one female and four males. Participants performed an exercise test on a Krogh cycle ergometer. A 10-min warm up at 55% of VO₂max preceded constant power tests to exhaustion that lasted up to approximately 8 min. Expired air was collected in Douglas bags throughout the exercise test. A balanced spirometer measured the expired air volume and gases were analyzed by the Haldane technique. At work rates that could be maintained 6.5 min, the VO₂ after 1 min of exercise was 84% of the value of the VO₂ at the first minute of exercise at an intensity that could be maintained approximately 2 min. The peak VO₂ was 2% higher at exercise work loads that can be maintained 6.5 min than for those that could be maintained 2 min. Gaesser and Poole (1996) have suggested that the slow component may be the reason VO₂max was elicited at submaximal work rates. They also noted that when work rate was plotted against time there was a slow component for work rates above the lactate threshold.

Henson et al. (1989) performed a study to determine whether the characteristics of the additional VO₂ component is a function of the absolute metabolic rate at which it occurs or rather a function of whether the exercise is above or below the estimated lactate threshold. Their participants were six men and six women. Each participant performed an incremental exercise test on a friction-braked cycle ergometer (Monark model 668, Varburg, Sweden) for determination of peak VO₂ and the estimate of the lactate threshold.
The estimated lactate threshold was defined as the highest VO2 which could be attained in an incremental test prior to the inflection point on the plot of VCO2 versus VO2. Each test began with a 4 min period of unloaded or "0" W pedaling, followed by a sequential increase in work rate of 15 W each minute for the women, or 25 W each minute for the men. Test were stopped when the participant could no longer maintain the pedal frequency and the VO2 at this point was defined as peak VO2. Participants also performed constant-load tests at work rates that were determined based on the previously determined lactate threshold to correspond to one or more work rates at or below the estimated lactate threshold and several work rates above the estimated lactate threshold. Work rates were selected based on an absolute increase (or decrease) in work rate above (or below) the estimated lactate threshold and were separated from each other by no more than 10% of the power at which peak VO2 was achieved. Tests began with a 4-min period of "0" W pedaling then the work rate was increased abruptly and maintained constant for 10 minutes or until the participant was unable to maintain the pedal frequency. During all exercise tests, ventilatory and gas exchange responses were monitored. Breath-by-breath VO2 was monitored using an integrated, computerized system. Estimated lactate threshold was defined as the point of intersection of the linear region of the slope of VCO2 plotted against VO2. Mean VCO2 corresponding to a given mean VO2 was determined by averaging individual data values over discrete intervals and the line of best fit for each region of the curve was determined by least-squares regression analysis. Results of the study by Henson et al. (1989) revealed that, below the lactate threshold, VO2 reached its steady-state value within 3 min. Steady-state VO2 at each work rate below the estimated lactate threshold
was generally higher than for the same work rate during incremental exercise; however, the slope of the VO₂-work rate relationship was not different for constant-load exercise below the estimated lactate threshold than that for the incremental tests.

**VO₂ kinetics at work rates above the lactate threshold**

The results of the study by Henson et al. (1989), (described above) revealed that, at work rates above the lactate threshold, VO₂ did not plateau during the 10 min of exercise. At work rates above the estimated lactate threshold, constant-load VO₂ following min 3 was greater than the predicted steady-state VO₂ for that work rate. As a consequence of this increase in VO₂, the same absolute work rate elicited a greater VO₂ response in participants for whom that work rate was above lactate threshold than in those for whom it was below lactate threshold. The results also indicated that at lower work rates above the lactate threshold, the VO₂ steady state was delayed and VO₂ rose above that predicted from the VO₂ work rate relationship lactate threshold. The elevation of VO₂ does not occur merely as a function of high absolute metabolic rates; rather it appears to be manifest at all work rates above the lactate threshold, irrespective of absolute VO₂ or work rate.

The purpose of the study by Roston et al. (1987) was to characterize the slow component of the exercise VO₂ kinetics at work rates above the lactate threshold, and to determine its relationship to the increase in blood lactate. Six healthy male participants, 27 to 45 years of age, performed an incremental cycle ergometer test to exhaustion with stages increasing 50 W per minute. Constant-load work rates were then selected, based on results from the incremental exercise test, such that the VO₂ might be expected to
plateau at a given percentage of the difference between the anaerobic threshold and the power at which VO$_2$max was elicited in the incremental test if the VO$_2$ kinetics above the lactate threshold were applicable to work rates above the lactate threshold. Each participant performed five to six constant-power tests each lasting 15 min, or less if the participant could not continue. The work rates were 90% of anaerobic threshold and anaerobic threshold plus 20, 40, 50 to 60, 60 to 70, and 70 to 80% of the difference. The results showed that a steady state was reached by 3 min for the subthreshold work rates, but at higher work rates, VO$_2$ tended to continue to increase after 3 min. The higher the work rate, the steeper the increase in VO$_2$. There was a significant correlation between the change in VO$_2$ from minute 3 to minute 6 and the lactate increase at minute 6. This change in VO$_2$ was greater as work rates approached VO$_2$max. It was also found that the rate of increase in lactate was proportionally greater as the magnitude of the work load increased. The results of this study suggest that VO$_2$ kinetics for a constant-load test can reasonably be predicted from results of the incremental exercise test. If the work rate being studied is below the participant’s lactate threshold, the change in VO$_2$ from minute 3 to minute 6 will be zero. However, above lactate threshold, the \( \Delta VO_2[6-3] \) increases as the work rate approaches the participant’s VO$_2$max. Because of the high correlation between the \( \Delta VO_2[6-3] \) and lactate increase at 6 min, it is therefore possible to tell from the VO$_2$ kinetics if a participant is working below or above lactate threshold. Also, the time course of the lactate increase and the slow phase of the VO$_2$ kinetics are similar.

The purpose of the study by Bason, Billings, Fox, and Gerke (1973) was to describe the VO$_2$ kinetics not only for different constant power work loads but also for
different simulated altitudes to investigate the effects of inspired hypoxia. Eight healthy male volunteers performed cycle ergometer exercise test at ground level (223 m) or at simulated altitudes of 2,286 and 3,810 m. The participants exercised at approximately 30, 60, and 80% of their ground level maximal aerobic power, once at each altitude. The participants exercised until exhausted or up to a maximum of 45 min. Bason et al. (1973) reported that the VO$_2$ responses were more rapid at higher exercise intensities. They also found that the time to reach steady state was related to the intensity of the work, being more delayed the greater the intensity. Bason et al. (1973) estimated that steady-state VO$_2$ was reached in 6 min for exercise at 30 and 60% of VO$_2$ max, independent of the altitude. The time constants were approximately 42 and 65 s, being considerably faster at the lower work rate. They also reported that at 30% of VO$_2$ max the O$_2$ uptake could be described by a single exponential function and at 60% for VO$_2$ max there would appear to be two distinct slopes which suggest that the O$_2$ uptake process could not be described by a single exponential function but required at least two functions, one fast and one slow, to describe the second increase in VO$_2$. Bason et al. (1973) concluded that the time to steady-state VO$_2$ is related only to the intensity of work, and is delayed at higher work rates.

Whipp and Wasserman (1972) conducted a study to determine the effect of work intensity on the kinetics of VO$_2$ in constant-load exercise. Five volunteer participants performed six 6 min exercise tests at 50, 75, 100, 125, 150, or 175 W in random order on different days. At 50, 75, and 100 W, the participants’ VO$_2$’s reached a stable value during the exercise and VO$_2$ increased approximately as a single exponential function with a half-time which ranged from 25 to 40 s, being somewhat faster at the lower work rates.
However, at work rates of 125, 150 and 175 W a stable value was not reached and the change of VO$_2$ could not be described by a single exponential function. A minimum of two components was required to fit the curves. At higher work rates, the steady-state time was greatly delayed and the rate of oxygen transport increased more slowly and could be mathematically described by a second exponential process.

In a study by Paterson and Whipp (1991), six participants performed constant-power exercise tests on a computer-controlled, electromagnetically braked cycle ergometer at a pedaling frequency of 60 to 70 rpm. Participants completed a series of constant power exercise tests at two work rates, one chosen to elicit a VO$_2$ of 90% of estimated lactate threshold and the second chosen to represent a power output midway between lactate threshold and VO$_2$max. Each test began with a 4-min warmup of unloaded pedaling followed by an abrupt increase to the appropriate intensity for a period of 6 min, and then abruptly decreased back to '0' W for 15 min recovery. Two to four repetitions of the protocols below the lactate threshold and above the lactate threshold were completed by each participant. To characterize the kinetic behavior of VO$_2$, the average response data of each participant were fitted by using various models; a mono-exponential (including a delay term), a model that considered the response to be comprised of two exponential components, and a model that considered there to be a mono-exponential component over the entire window, but upon which an additional, delay component was subsequently superimposed. In the third model, the mono-exponential phase of the fitting (i.e. '3 min fit') was extrapolated to 6 min to establish the steady-state equivalent of this exponential component. Comparison between models was based on the residual mean square of the
time constant for VO\(_2\) using paired t test with significance levels set at \(p < 0.05\). The participants had a mean VO\(_{2}\)\(_{\text{max}}\) of 2.9 \(l\cdot\text{min}^{-1}\) or 43 \(ml\cdot\text{kg}^{-1}\cdot\text{min}^{-1}\) and lactate threshold averaged 60% of VO\(_{2}\)\(_{\text{max}}\). VO\(_2\) kinetics at work rates above the lactate threshold appeared to be more complex with a steady state not attained within 6 min of exercise. Above the lactate threshold using a two-component model, the early component (i.e. 3-min fit) clearly yielded a better representation of the early kinetic phase of the response; in no case did the 6 min one component fit adequately describe the kinetics. The early mono-exponential response elicited the best-fit time constant of 44 s. At intensities above the lactate threshold the time constant was than at work rate below the lactate threshold. Patterson and Whipp (1991) could not discriminate between an exponential or linear fit to the slow phase of the VO\(_2\) response. A continuous double-exponential fit for exercise above the lactate threshold yielded a poor fit to the data with a rapid-component time constant of 17 s in four of the six participants. Evidence of a greater residual mean square error showed a significantly poorer fit for the 6-min fit of exercise above the lactate threshold. The early component of a two-component model represented the early kinetic phase best. The difference in the change in VO\(_2\) and the change in work rate for the six participants below lactate threshold and to the end of the first-component (3-min) fit above lactate threshold were not significantly different at approximately 9.5 \(ml\cdot\text{min}^{-1}\cdot\text{W}^{-1}\). The second component of the two compartment fit, from 3 to 6 min, showed a significant slow phase of increase in VO\(_2\) of 230 \(ml\cdot\text{min}^{-1}\) during the suprathreshold exercise. There was no 'slow component' increase of VO\(_2\) in the sub-threshold exercise. Even using only the '3 min fit' for the exercise above the lactate threshold, the time constant was significantly
longer (40 s) than for the exercise below the lactate threshold (31 s).

**Modeling for VO₂ Slow Component**

There is no consensus as to whether the VO₂ slow component conforms best to an exponential or linear model. The VO₂ slow component may be different at different exercise intensities. Barstow and Molé (1991) found evidence of both an exponential and a linear slow component in different participants for exercise bouts of 8 min, whereas Patterson and Whipp (1991) were unable to distinguish between exponential and linear fits.

Casaburi, Barstow, Robinson, and Wasserman (1989) sought to determine whether there was a range of exercise intensities over which VO₂, VCO₂, and VO₂ kinetics are substantially constant. Four volunteers performed a total of 162 constant power cycle ergometer exercise studies. Subsequent exercise tests consisted of at least 3 min of unloaded pedaling followed by 10 min of exercise at a constant work rate. Participants exercised at one of seven work rates, the lower six of which were spaced evenly below their previously determined highest work rate. Casaburi et al. (1989) attempted to fit the VO₂ response to four mathematical models. The models used were:

1) \( \text{VO}_2(t) = \text{VO}_2 b + [(\text{VO}_2 f - \text{VO}_2 b) \cdot (1-e^{-t/\tau})] \),

2) \( \text{VO}_2(t) = \text{VO}_2 b + [(\text{VO}_2 f - \text{VO}_2 b) \cdot (1-e^{(-t/T)})] \),

3) \( \text{VO}_2(t) = \text{VO}_2 b + [(\text{VO}_2 SS - \text{VO}_2 b) \cdot (1-e^{-t/T})] + [(\text{VO}_2 f - \text{VO}_2 SS) \cdot (1-e^{-t/T})] \), and

4) \( \text{VO}_2(t) = \text{VO}_2 b + [(\text{VO}_2 SS - \text{VO}_2 b) \cdot (1-e^{(-t/T)})] + S(t-T_D) \).

\( \text{VO}_2 b \) is VO₂ baseline or the VO₂ immediately before the start of exercise. Even though a steady state is not present with a slow component, VO₂ steady state (VO₂SS) is what the
VO₂ would be if a slow component did not occur. The maximal VO₂ obtained during each exercise test is referred to as VO₂ final (VO₂ f).

The first and simplest is a single-exponential model fit to the data extending from the time at which work rate was increased through the seventh min. The second mathematical model omits the phase I period from the data fit and features both an exponential component and a time delay. Casaburi et al. (1989) sought to determine whether a slow exponential component was present by fitting each data set to model 3, which is the sum of two exponential components. When model 3 parameter values converged to a very long second time constant, the presumption was made that a linear "drift" was a preferable description. For these data sets, the expression denoted model 4 was used that contained a single-exponential component and a linear term, the slope of which was calculated as the model 3 second-exponential component. Results showed that the time constant for VO₂ increased markedly at the higher exercise intensities. The exercise intensities associated with markedly prolonged VO₂ kinetics are associated with substantially elevated blood lactate levels. Highly significant correlations were observed between the increase in end-exercise lactate over resting levels and τVO₂ (r = 0.70, p < 0.005). These data showed that there was a significant trend for VO₂ kinetics to be slower at higher work rates even when the work rates are not associated with a sustained increase in blood lactate. However, the slope of the time constant for VO₂ change with exercise intensity was appreciably higher at work rates associated with lactic acidosis (0.27 vs. 0.16 s/W). The trend for work rates not associated with lactic acidosis equates to the time constant for VO₂ being 12 s faster for a transition from unloaded cycling to 25 W than for
a transition from unloaded cycling to 100 W. VO$_2$ kinetics were consistently better fit by a two-exponential model (model 3) at work rates associated with elevated blood lactate. The model 3 parameters for VO$_2$ at higher work intensities were composed of a rapid response component with a time constant averaging 20 s and a time delay averaging 8 s; these values did not change appreciably with change in work rate. The fractional contribution of the slower response component (A$_2$/A$_1$) tended to increase with the increasing work rate and the time constant of response (z2) tended to become longer. The VO$_2$ responses at lower work rates tended to be better fit by models featuring a single exponential plus a time delay and were sometimes associated with an additional small upward slope.

Barstow and Molé (1991) contrasted parameter estimates derived from 2 models. The first model used two exponential terms that began after a common time delay.

$$\Delta VO_2(t) = A_1 [1-e^{-(TD)/z1}] + A_2 [1-e^{-(TD)/z2}]$$

The second model contains a second exponential term that starts after a second independent time delay.

$$\Delta VO_2(t) = A_1 [1-e^{-(TD)/z1}] + A_2 [1-e^{-(TD)/z2}]$$

The A$_1$ is the same as (VO$_2$SS - VO$_2$b) and A$_2$ is the same as (VO$_2$f - VO$_2$SS) that Casaburi et al. (1989) used. Participants were four trained male cyclists ages 23 to 38 yr. All testing was conducted between 6 and 10 A.M., at the same time of day for a given participant. Exercise tests were performed on an electronically-braked cycle ergometer (Quinton model 844). Preliminary testing involved an incremental work test (increase of 33 W every minute) to exhaustion to determine VO$_2$max and the lactate threshold. Gas
exchange was measured on a breath-by-breath basis. From these results, four work rates were chosen for each participant; two were below the lactate threshold, representing moderate exercise (35 and 55% VO₂max), and two were above the lactate threshold, representing heavy exercise (85 and 100% VO₂max). The constant work rate tests consisted of 4 min of baseline pedaling at 33 W, then 8 min at one of the four work rates selected for the participant, followed by 10 min of recovery at 33 W. Two tests were performed in one day, the first being one of the two moderate work rates, followed by 30 min of rest and then one of the heavy exercise tests. Exercise at each work rate was performed four times. Paired t-tests were used to compare parameter estimates from models 1 and 2. Linear regression was used to evaluate the linearity of the amplitude of the VO₂ response as a function of work rate. Analysis of variance with repeat measures was used to discern any differences in time constants of the primary VO₂ response (τ₁) among the four work intensities. Finally, a t-statistic was calculated to compare slopes of regression lines. A significance level was declared at $p < 0.05$. Results indicated that in 2 to 3 min a steady state was attained at exercise intensities below the lactate threshold but the slow upward movement of VO₂ and delayed or absent steady state when the exercise intensity was above the lactate threshold. Responses to the moderate work intensities below the $T_{\text{LAC}}$ were initially fit with model 1 to test for the possible presence of higher exponential components. In all eight cases (2 work rates in each of 4 participants), the two time constants (τ₁ and τ₂) converged to a common value, confirming the monoexponentially of each response. In only one of the eight responses to exercise above the lactate threshold did the two-exponential model regression reduce to a single exponential.
In the other seven, discrete parameter values for the two components emerged. Barstow and Molé (1991) stated that the mono-exponential model described the response of exercise above the lactate threshold fairly well. However, there was a slight but noticeable trend to the residuals between 60 and 200 s. On the other hand, the residuals for model 2 appear randomly distributed around zero throughout the exercise period, with no trend, and the delay in onset of the second exponential term was readily apparent around 180 s. This implied that the second component which occurred later in exercise did not begin at the same time as the first which occurred soon after exercise onset. There was no significant difference ($p > 0.05$) between the slopes for the two regression equations which that calculated for $A_i$ and net work rate for exercise below the lactate threshold ($A_i = -75 + 11.5 \text{ net work rate}, r = 0.962$) and above lactate threshold ($A_i = 339 + 8.3 \text{ net work rate}, r = 0.717$). This analysis suggests that the amplitude of the primary $\text{VO}_2$ component ($A_i$) increases approximately linearly with exercise. In addition, these findings suggest that the additional $\text{VO}_2$ observed for exercise above the lactate threshold is primarily associated with the slower $\text{VO}_2$ component. Analysis of variance revealed no significant differences among the value of $\tau$ for the four different work rates, although there was a tendency for $\tau$ to increase at the highest work rate. The proportional increase seen for $A_i$ and invariant $\tau$ for increasing work intensities implied that the fast component of $\text{VO}_2$ in these trained cyclist behaves as an approximately linear first-order system, even for work above the lactate threshold. Using model 1, $\tau$, constrained a priori to begin coincident with the faster term, rose $10.1 \pm 3.1 \text{ s after the onset of exercise}$. In contrast, model 2 showed that the slower component began on average $105.0 \pm 46.0 \text{ s into exercise} (p < 0.005)$.
compared with model 1). There was no difference in the estimates for the slower time constant ($\tau$) between the two models ($155.2 \pm 37.1$ versus $138.2 \pm 5$, model 1 versus model 2, $p > 0.05$). However, model 2 predicted a smaller asymptote for the slower exponential term ($A_2$) ($0.88 \pm 0.38 \text{ l-min}^{-1}$) relative to that estimated by model 1 ($1.51 \pm 0.56 \text{ l-min}^{-1}$, $p < 0.005$). Using model 2 results, accounted for $19 \pm 4\%$ of the total increase in VO$_2$ for work rate 3 ($n = 4$) and $34 \pm 6\%$ for work rate 4 ($n = 3$). In conclusion, Barstow and Molé (1991) found that the metabolic cost of exercise (as $\Delta$VO$_2$/\Delta$work rate) rose linearly for work below the lactate threshold. However, as work intensity increased above the lactate threshold, both the end-exercise VO$_2$ and extrapolated "steady state" plateau (as the sum of $A_1 + A_2$) was greater than that predicted from responses below the lactate threshold. This nonlinear increase in VO$_2$ with heavy (above the lactate threshold) exercise can be largely attributed to the appearance of a second slower component.

Hill, et al (1997) also examined the kinetics for the test at 92% and 100% of Vmax. For each test, rolling eight-breath averages of data from the first 2 minutes and 5 minutes of exercise were fit to a monoexponential model, $\text{VO}_2(t) = \text{VO}_2\text{initial} + (\text{VO}_2\text{max} - \text{VO}_2\text{initial}) \cdot (1 - e^{-\tau})$. Hill et al (1997) also tried to fit the data to a bi-exponential model and an exponential-plus-linear model, each with a delay before the slow component. In addition to the two models, the difference between VO$_2$ in the third and sixth minute were calculated. Hill et al (1997) found that, at the faster velocity, the response was faster (i.e., $\tau$ being smaller). Predicted values for VO$_2$max at both velocities were lower than those actually achieved although, at the 92% of Vmax, the predicted value approached the actual value as
more data were used in its derivation. The two-component models did not describe the response for either of the velocities. However, visual inspection of the individual responses and with the difference between VO₂ in the third and sixth minutes at 92% of Vmax may suggest there might be a slow component to the response.

The purpose of the study by Casaburi et al. (1989) was to determine if there is a range of exercise intensities over which Vₑ, VCO₂, VO₂ kinetics are substantially constant. Four participants performed an incremental test and a total of 162 constant power test on a cycle ergometer. The incremental test began with 4 min of unloaded cycling followed by increases of 25 W·min⁻¹ for participants 1 and 2 and 20 W·min⁻¹ for participants 3 and 4. The constant power test consisted of at least 3 min of unloaded cycling followed by 10 min of exercise at a constant work rate. Tests were separated by at least 45 min and 90 min for the heavy intensities. Blood samples were taken within 1 min of the end of exercise at the end of one trial of each work rate. The data from the test were fit to three models. The data from the time when the work rate was increased to the seventh minute of exercise were fit to the mono-exponential model. Model two fits the data to both an exponential component and a time delay. Casaburi et al. (1989) found an average of 18.6 ± 5.6 s for the duration of phase I kinetics (described by Whipp, 1994). The shorter durations for phase I kinetics were associated with the higher intensities. Finally, they tried to fit the data to model three which was the sum of two exponential components or model 3a which had a mono-exponential component and a linear term. Casaburi et al. (1989) found highly significant correlations between increases in end-exercise lactate over resting levels and both τ VO₂ and τVₑ (r = 0.70, p < 0.05; r = 0.52, p < 0.01,
respectively). A trend analysis using linear regression was performed on the time constant at work rates that were not associated with blood lactate. "The regression slope of the relationship (in s/W) of $\tau V_O_2$, $\tau V_CO_2$, and $\tau V_E$ for work rate are 0.16, 0.04, and 0.03, respectively." (p 550). $\tau V_O_2$ work rate slope was significantly different from zero ($p < 0.01$). However the slope of $\tau V_O_2$ was higher at work rates associated with lactic acidosis (0.27 vs. 0.16 s/W). At the lower intensities, the $V_O_2$ kinetics were best described by the mono-exponential model. At work rates associated with elevated blood lactate, the $V_O_2$ kinetics were better fit by a two component model. A time constant of 20 s and a time delay of 8 s was found using model three for the higher work rates. It was found that at the higher intensities there was a second exponential component which became more prolonged with increasing work intensities. $V_CO_2$ kinetics were best fit by model 2 featuring a single exponential term with a delay. The time constant and time delay for model two was similar to the model 1 time constant (which denotes the "mean response time") for all variables.

In summary, studies have indicated that $V_O_2_{max}$ can be elicited over a range of severe intensities. At intensities above the lactate threshold a satisfactory mathematical description of the slow component has yet to be provided. It is clear that intensity (when it ranges from moderate to severe) affects $V_O_2$ kinetics, primarily because of the imposition of a slow component at "heavy" intensities and at certain "severe" intensities. But it is not so clear whether velocity per se (e.g., separate from the presence or absence of lactic acid production, or a slow component) affects the response.
CHAPTER III

METHODS AND MATERIALS

The procedures employed to determine VO$_2$max, Vmax, and VO$_2$ kinetics are discussed in this section. Participant characteristics, the process of recording the metabolic responses during testing, methods of determining treadmill speeds, and statistical methods employed for analysis of data are other topics of discussion in this section.

Overview

Vmax was calculated as the speed at which VO$_2$max is elicited in an incremental test. Each participant participated in five tests at different percentages of Vmax (95%, 100%, 105%, and 110%). All tests were separated by at least 24 hours. For each test time to exhaustion (T$_{lim}$) and various measures of kinetics were calculated, responses at the 4 velocities were compared.

Participant Characteristics

Participants were 17 volunteers, both male (10) and female (7), who ran 25 or more kilometers per week. All individuals provided voluntary, written informed consent (Appendix A) prior to data collection. Participant's age, height, and weight were recorded before every test and are reported in Table 1.
Table 1

Mean (+) Participant Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Vmax (m/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>26 ± 6</td>
<td>173.4 ± 9.9</td>
<td>71.0 ± 13.3</td>
<td>272.2 ± 32</td>
</tr>
<tr>
<td>Men</td>
<td>27 ± 7</td>
<td>180 ± 6</td>
<td>80 ± 11</td>
<td></td>
</tr>
<tr>
<td>Women</td>
<td>23 ± 2</td>
<td>165 ± 8</td>
<td>59.5 ± 4</td>
<td></td>
</tr>
</tbody>
</table>

Data Collection Procedures

Calculation of VO₂max and Vmax

All participants performed an incremental treadmill test in order to directly determine VO₂max, VCO₂max, Vₚmax, and Vmax. Incremental tests were performed until exhaustion at a 0% slope on a treadmill (Quinton 633). The initial speed was set at 8 km·h⁻¹ for the female participants and 10 km·h⁻¹ for the male participants. All stages were 1-min in duration and the speed was increased by 1 km·h⁻¹ until the participants reached exhaustion. All treadmill speeds were verified by stopwatch recordings of 20 belt revolutions. Heart rates were monitored using a Marquette Max®-1 Stress System (Milwaukee, Wisconsin). During each stage of exercise, heart rate was recorded from a five-lead EKG.

Expired gases were collected continuously during all tests with the use of a CPX metabolic cart (Medical Graphics Inc., St. Paul, MN). Prior to each test, calibration of the pneumotach was performed using a calibrated 3 liter syringe. O₂ and CO₂ analyzers
were calibrated according to the manufacturer's instructions using gases of known concentration. $\text{VO}_2$, $\text{VCO}_2$, $\text{V}_E$, and RER were obtained on a breath-by-breath basis. Breath-by-breath data were reduced to 15-s averages from which rolling 30-s averages were calculated. $\text{VO}_2\text{max}$ was determined as the highest 30-s average. Similarly, the highest 30-s average for $\text{V}_E$, $\text{VCO}_2$, and RER were taken as $\text{V}_E\text{max}$, $\text{VCO}_2\text{max}$, and maximal RER. The highest $\text{VO}_2$ was accepted as $\text{VO}_2\text{max}$ if it was associated with a respiratory exchange ratio above 1.1. $\text{Vmax}$ was calculated as the intensity at which the participant first reached $\text{VO}_2\text{max}$.

$T_{\text{LIM}}$ and other responses at $\text{Vmax}$

Participants performed constant power tests at 100%, 100%, 110%, 105%, and 95% of $\text{Vmax}$, each on a separate day in that order. The first test at 100% served as a practice trial. Each test began with a 6 min warm up at either 50% or 60% of $\text{Vmax}$. Therefore the first warmup for the first group was at 50% of $\text{VO}_2\text{max}$ and the first warmup for the second group was at 60% of $\text{VO}_2\text{max}$. Following the warm up, participants rested for 5 min. During this rest period, treadmill speed was set at $\text{Vmax}$ or a given percentage of $\text{Vmax}$. The treadmill velocity was verified during the test by timing 20 treadmill belt revolutions. As with the incremental test, expired gases were analyzed on a breath-by-breath basis, 15-s means were calculated, and 30-s rolling averages were recorded. $\text{VO}_2\text{max}$, $\text{VCO}_2\text{max}$, $\text{V}_E\text{max}$, and maximal RER were recorded as the highest 30-s rolling average.

Determination of time to and time at $\text{VO}_2\text{max}$

Print-outs of all tests were visually inspected in order to determine the time to
achieve $\text{VO}_2\text{max}$ and the time that $\text{VO}_2\text{max}$ was sustained. The time to $\text{VO}_2\text{max}$ was determined as the time from the onset of exercise until the middle of the first 15-s period in which $\text{VO}_2\text{max}$ was equal to or greater than the 30-s $\text{VO}_2\text{max}$ value. The time that $\text{VO}_2\text{max}$ was sustained was calculated as the time at which $\text{VO}_2\text{max}$ was achieved until the time the test was terminated. In each case, "$\text{VO}_2\text{max}$" refers to the highest $\text{VO}_2$ achieved in the particular test.

$\text{VO}_2$ kinetics

The breath by breath metabolic data collected during the final stage of each constant power test were reduced to rolling eight-breath averages. These data were fit to models similar to those used by Casaburi et al. (1989). These models include:

- A simple mono-exponential model;
  \[ \text{VO}_2(t) = \text{VO}_2 b + [(\text{VO}_2 f - \text{VO}_2 b) \cdot (1-e^{(-t/\tau)})], \]

- A simple mono-exponential model with a delay,
  \[ \text{VO}_2(t) = \text{VO}_2 b + [(\text{VO}_2 f - \text{VO}_2 b) \cdot (1-e^{(-t-D)/\tau})]; \]

- A bi-exponential model with delay on second exponential response model,
  \[ \text{VO}_2(t) = \text{VO}_2 b + [(\text{VO}_2 SS - \text{VO}_2 b) \cdot (1-e^{(-t-d)/\tau})] + [(\text{VO}_2 f - \text{VO}_2 SS) \cdot (1-e^{(-t-d2)/\tau})]; \]

- An exponential-plus-linear model,
  \[ \text{VO}_2(t) = \text{VO}_2 b + [(\text{VO}_2 SS - \text{VO}_2 b) \cdot (1-e^{(-t-D)/\tau})] + S(t-T_D). \]

Iterative nonlinear regression on SPSS (Chicago, IL, USA) was used to derive values for the time constant ($\tau$) and expected $\text{VO}_2\text{max}$. For two component models, a value for the $\text{VO}_2SS$ was derived and the delay and slope or $\tau$ of the slow component were derived. The program also generated a standard error of the estimate (SEE) for each parameter and
an $R^2$ value. The criteria for accepting values from a model were $R^2 \geq 0.90$, and SEE of each parameter was $\leq 10\%$ of the parameter estimate.

**Statistical Analysis**

Data from 5 test conditions (the incremental 95%, 100%, 105%, and 110% of $V_{\text{max}}$) were analyzed using a one-way ANOVA to detect differences and a linear component. Planned comparison tests were used to locate test differences. A one-way ANOVA and planned comparison tests were used to compare the effect of velocity on time to max, $\tau$, time at max, and predicted $V_{O_2\text{max}}$ in the constant velocity test. A significance level was set at $p \leq 0.01$. 
CHAPTER IV

RESULTS

The purpose of this study was to evaluate the effect of intensity on VO$_2$ kinetics in response to exercise over a range of severe exercise intensities. The results of this study are presented in this chapter.

Responses to incremental and constant velocity test

The responses to the incremental tests and constant velocity tests at 95%, 100%, 105%, and 110% of V$_{\text{max}}$ are presented in Table 2. Included in this table are the mean values and the results of the repeated measures ANOVA across the five trials. Mean values for VO$_2$$_{\text{max}}$ in constant velocity tests were not different ($F_{4,64} = 1.11, p = 0.36$) from the criterion measure for VO$_2$$_{\text{max}}$ determined in the incremental test.

Similarly, no differences were found across trials in VCO$_2$$_{\text{max}}$ ($F_{4,64} = 1.06, p = 0.38$) and V$_e$$_{\text{max}}$ ($F_{4,64} = 3.15, p = 0.02$). However values for RER$_{\text{max}}$ ($F_{4,64} = 6.12, p = 0.01$) were different in the constant power test.
Table 4c.

**Kinetics of the VO₂ responses at different velocities obtained using the mono-exponential model (2 minutes)**

<table>
<thead>
<tr>
<th></th>
<th>95% (N = 16)</th>
<th>100% (N = 13)</th>
<th>105% (N = 12)</th>
<th>110% (N = 10)</th>
<th>Post hoc&lt;sup&gt;†&lt;/sup&gt; Comparison</th>
<th>ANOVA Difference</th>
<th>Linear Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau ) (s)</td>
<td>39&lt;sup&gt;a&lt;/sup&gt; ± 7</td>
<td>33&lt;sup&gt;ab&lt;/sup&gt; ± 6</td>
<td>32&lt;sup&gt;b&lt;/sup&gt; ± 6</td>
<td>32&lt;sup&gt;b&lt;/sup&gt; ± 6</td>
<td>a b b b</td>
<td>( p = 0.0001 )</td>
<td>( F_{4,43} = 4.21 )</td>
</tr>
<tr>
<td>SEE( \tau )</td>
<td>2 ± 1.11</td>
<td>2 ± 1.33</td>
<td>2 ± 0.92</td>
<td>2 ± 1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predicted VO₂max (ml·min&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>3201&lt;sup&gt;a&lt;/sup&gt; ± 737</td>
<td>3320&lt;sup&gt;a&lt;/sup&gt; ± 771</td>
<td>3190&lt;sup&gt;a&lt;/sup&gt; ± 830</td>
<td>3090&lt;sup&gt;a&lt;/sup&gt; ± 763</td>
<td>a a a a</td>
<td>( p = 0.25 )</td>
<td>( F_{4,43} = 1.41 )</td>
</tr>
<tr>
<td>SEE</td>
<td>56 ± 5</td>
<td>56 ± 36</td>
<td>48 ± 36</td>
<td>57 ± 36</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.94 ± 0.03</td>
<td>0.92 ± 0.06</td>
<td>0.93 ± 0.02</td>
<td>0.92 ± 0.04</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Values are given as mean ± standard deviation

Means with similar superscripts were not different based on planned comparisons significance \( p \leq 0.01 \)

§ Means with similar superscripts were not different based on planned comparisons significance \( p \leq 0.05 \)
Responses at Different percentages of Vmax

Mean values for responses at 95%, 100%, 105%, and 110% of Vmax are presented in Table 3, along with the results of repeated measures ANOVA and planned comparisons tests. The responses at each of the four intensities are graphed for one participant and presented in Appendix B.

By design, the actual mean treadmill velocities were significantly different \((p = 0.01)\), and, as expected the mean values for \(T_{LIM}\) were significantly different \((p = 0.01)\). No significant difference was found for \(V_{O_2\max}\) at from the four constant velocity test \((p = 0.28)\). Both the time to and time at \(V_{O_2\max}\) were significantly different and tended to decrease in a linear fashion as velocity increased. Therefore, time to \(V_{O_2\max}\) was significantly less at 110% of Vmax \((90 \pm 35\ s)\) than at 95% of Vmax \((224 \pm 87\ s)\).

KINETICS

The kinetic responses derived from the mono-exponential model with and without a delay for all the \(V_{O_2}\) data, and data from the first two minutes of \(V_{O_2}\) response are presented in Tables 4a, b, and c. Included are the mean values for the time constant \((\tau)\), the \(\text{SEE} of \tau\), predicted \(V_{O_2\max}\), the \(\text{SEE} of V_{O_2\max}\) and \(R^2\).

\(\tau\) and predicted \(V_{O_2\max}\)

Results from the ANOVA indicate that there was no difference or linear effect in predicted \(V_{O_2\max}\) when using the mono-exponential model with all the data \((p = 0.34, p = 0.08)\) or with 2 minutes of data \((p = 0.37, p = 0.17)\). However there was a difference and linear effect in \(\tau\) when using the mono-exponential model with all the data \((p = 0.01, p = 0.01)\) and 2 minutes of data \((p = 0.01, p = 0.01)\). The mono-exponential model worked for
more participants at the longer test, 95% of Vmax, (N = 15) than the shorter test, 110% of Vmax, (N = 8). The results of the ANOVA for the mono-exponential model with a delay were similar to the results with out a delay. Similarly, there was no difference or linear effect in predicted VO$_2$max ($ p = 0.76, p = 0.61$) and there was a difference and a linear effect for $\tau$ ($ p = 0.01, p = 0.01$). It was also revealed that there was not a difference in the delays at the different velocities ($ p = 0.04$), but there was a linear effect on the delay ($ p = 0.01$). The mono-exponential model with the delay was more successful at fitting more participants data to the model than the mono-exponential model with out the delay.
# Table 4b.

| Kinetics of the VO₂ responses at different velocities obtained using the mono-exponential model with a delay |
|---|---|---|---|---|---|
| | 95% | Velocity as a percentage of Vmax | 105% | 110% | Post hoc\(|p| ≤ 0.05|
| (N = 15) | (N = 15) | (N = 15) | (N = 16) |
| \(τ\) (s) | 29\(±\) 5 | 22\(±\) 4 | 21\(±\) 4 | 18\(±\) 4 | a b bc c |
| SEE | 0.82 \(±\) 0.33 | 0.66 \(±\) 0.21 | 0.73 \(±\) 0.40 | 0.90 \(±\) 0.69 | |
| Delay (s) | 7\(±\) 4 | 9\(±\) 4 | 9\(±\) 2 | 10\(±\) 3 | a b b |
| SEE | 0.58 \(±\) 0.23 | 0.43 \(±\) 0.12 | 0.43 \(±\) 0.20 | 0.50 \(±\) 0.26 | |
| Predicted VO₂max (ml·min\(^{-1}\)) | 3128\(±\) 710 | 3080\(±\) 783 | 3242\(±\) 660 | 2992\(±\) 744 | a a a |
| SEE | 9 \(±\) 4 | 11 \(±\) 6 | 15 \(±\) 10 | 20 \(±\) 12 | |
| R\(^2\) | 0.97 \(±\) 0.02 | 0.97 \(±\) 0.02 | 0.97 \(±\) 0.02 | 0.97 \(±\) 0.02 | |
| MRT | 36.4\(±\) 4 | 31.3\(±\) 4 | 29.9\(±\) 5 | 28.4\(±\) 4 | a b bc c |
| SEE | 0.81 | 0.97 | 0.78 | 0.80 | |

Values are given as mean ± standard deviation

Means with similar superscripts were not different based on planned comparisons significance \(p ≤ 0.01\)

\(\$\) Means with similar superscripts were not different based on planned comparisons significance \(p ≤ 0.05\)
Table 4a.

**Kinetics of the VO$_2$ responses at different velocities obtained using the mono-exponential model (no delay)**

<table>
<thead>
<tr>
<th></th>
<th>95% (N = 15)</th>
<th>100% (N = 13)</th>
<th>105% (N = 10)</th>
<th>110% (N = 8)</th>
<th>Post hoc $^\S$</th>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity as a percentage of Vmax</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau$ (s)</td>
<td>37$^a$ ± 5</td>
<td>32$^b$ ± 5</td>
<td>32$^b$ ± 4</td>
<td>31$^b$ ± 6</td>
<td>a b b</td>
<td>$p = 0.0001$</td>
</tr>
<tr>
<td>SEE$\tau$</td>
<td>1 ± 0.35</td>
<td>1 ± 0.57</td>
<td>1.27 ± 0.57</td>
<td>2 ± 0.94</td>
<td></td>
<td>$F_{4,39} = 7.21$</td>
</tr>
<tr>
<td>Predicted VO$_2$max (ml·min$^{-1}$)</td>
<td>3162$^a$ ± 706</td>
<td>3222$^a$ ± 788</td>
<td>3217$^a$ ± 750</td>
<td>2991$^a$ ± 49</td>
<td>a a a</td>
<td>$p = 0.02$</td>
</tr>
<tr>
<td>SEE</td>
<td>12 ± 5.79</td>
<td>20 ± 13</td>
<td>31 ± 17</td>
<td>45 ± 26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.95 ± 0.03</td>
<td>0.94 ± 0.02</td>
<td>0.94 ± 0.02</td>
<td>0.94 ± 0.02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Values are given as mean ± standard deviation

Means with similar superscripts were not different based on planned comparisons significance $p \leq 0.01$

§ Means with similar superscripts were not different based on planned comparisons significance $p \leq 0.05$
TABLE 3.

Responses to Constant Velocity Tests  $p \leq 0.01$

<table>
<thead>
<tr>
<th></th>
<th>95%</th>
<th>Velocity as a percentage of Vmax</th>
<th>Post hoc $^\delta$</th>
<th>ANOVA</th>
<th>Linear effect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100%</td>
<td>105%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>110%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^\ast$N = 16  $^+$N = 15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{VO}_2\text{max} \ (\text{ml} \ \text{min}^{-1})$</td>
<td>$3180^a \pm 734$</td>
<td>$3102^a \pm 769$</td>
<td>$3130^a \pm 728$</td>
<td>$3020^a \pm 727$</td>
<td>a a a</td>
</tr>
<tr>
<td>$V_{c\text{max}} \ (\text{l} \ \text{min}^{-1})$</td>
<td>$125^a \pm 25$</td>
<td>$130^b \pm 27$</td>
<td>$129^{ab} \pm 29$</td>
<td>$128^{ab} \pm 25$</td>
<td>a b b ab</td>
</tr>
<tr>
<td>$\text{VCO}_2\text{max} \ (\text{l} \ \text{min}^{-1})$</td>
<td>$4292^a \pm 921$</td>
<td>$4400^a \pm 1143$</td>
<td>$4547^a \pm 1018$</td>
<td>$4310^a \pm 1101$</td>
<td>a a a a</td>
</tr>
<tr>
<td>RERmax</td>
<td>$1.38^a \pm 0.07$</td>
<td>$1.45^a \pm 0.12$</td>
<td>$1.47^{ab} \pm 0.12$</td>
<td>$1.56^a \pm 0.15$</td>
<td>a ab bc c</td>
</tr>
<tr>
<td>$T_{\text{lim}} \ (\text{s})$</td>
<td>$301^a \pm 148$</td>
<td>$229^b \pm 121$</td>
<td>$169^c \pm 87$</td>
<td>$126^{de} \pm 42$</td>
<td>a b c c</td>
</tr>
<tr>
<td>TTmax (s)</td>
<td>$224^a \pm 87$</td>
<td>$179^{ab} \pm 92$</td>
<td>$135^{bc} \pm 85$</td>
<td>$90^c \pm 35$</td>
<td>a b c d</td>
</tr>
<tr>
<td>Tamax (s)</td>
<td>$77^a \pm 87$</td>
<td>$50^{ab} \pm 45$</td>
<td>$33^{b} \pm 30$</td>
<td>$36^{de} \pm 18$</td>
<td>a ab b b</td>
</tr>
<tr>
<td>Velocity (m: min$^{-1}$)</td>
<td>$257 \pm 28$</td>
<td>$271 \pm 28$</td>
<td>$285 \pm 31$</td>
<td>$298 \pm 31$</td>
<td>a b c d</td>
</tr>
</tbody>
</table>

Values are given as mean ± standard deviation.

Means with similar superscripts were not different based on planned comparisons significance $p = 0.01$.

$^\delta$ Means with similar superscripts were not different based on planned comparisons significance $p = 0.05$.

$T_{\text{lim}}$ - time to exhaustion.

TTmax - time to achieve $\text{VO}_2\text{max}$.

Tamax - time $\text{VO}_2\text{max}$ was sustained.
### TABLE 2.

**Responses to Incremental and Constant Velocity Tests  
 \( p \leq 0.01 \)**

<table>
<thead>
<tr>
<th></th>
<th>Incremental</th>
<th>95%</th>
<th>100%</th>
<th>105%</th>
<th>110%</th>
<th>ANOVA(^g) ( p &lt; 0.05 )</th>
<th>Tukey post hoc ( p )</th>
</tr>
</thead>
</table>
| VO\(_2\)\(_{\text{max}}\)  
(\(\text{ml}\cdot\text{min}^{-1}\)) | 3182\(^a\) ± 804 | 3180\(^a\) ± 734 | 3102\(^a\) ± 769 | 3130\(^a\) ± 728 | 3020\(^a\) ± 727 | a a a a a |  
| V\(_e\)\(_{\text{max}}\)  
(\(\text{l}\cdot\text{min}^{-1}\)) | 132\(^a\) ± 27 | 125\(^b\) ± 25 | 130\(^{ab}\) ± 27 | 129\(^{ab}\) ± 29 | 128\(^{ab}\) ± 25 | a b ab ab ab |  
| RER\(_{\text{max}}\) | 1.43\(^{ab}\) ± 0.13 | 1.38\(^a\) ± 0.07 | 1.45\(^{ab}\) ± 0.12 | 1.47\(^b\) ± 0.12 | 1.56\(^b\) ± 0.15 | ac a ab bc b |  
| VCO\(_2\)\(_{\text{max}}\)  
(\(\text{ml}\cdot\text{min}^{-1}\)) | 4442\(^a\) ± 993 | 4292\(^a\) ± 921 | 4400\(^a\) ± 1143 | 4547\(^a\) ± 1018 | 4310\(^a\) ± 1101 | a a a a a |  

*Values are given as mean ± standard deviation*

*Means with similar superscripts were not different based on planned comparisons significance \( p = 0.01 \)*

\(^g\)Means with similar superscripts were not different based on planned comparisons significance \( p = 0.05 \)
CHAPTER V

DISCUSSION AND CONCLUSIONS

The purpose of this study was to evaluate the effect of intensity on kinetics over a range of severe intensities. Participants performed 5 constant velocity tests at 100%, 100%, 110%, 105%, and 95% of their individually determined Vmax. In these tests, \( \tau \), VO\(_2\)max, time to achieve VO\(_2\)max, and time VO\(_2\)max could be sustained were determined. The VO\(_2\) response at the different constant velocity test were also fit to four mathematical models: a single-exponential model with and without a delay, a bi-exponential model with a delay on the second exponential response model, and an exponential-plus linear model.

The first finding was that a VO\(_2\) equal to the criterion measure for VO\(_2\)max in an incremental test was achieved at 95%, 100%, 105%, and 110% of Vmax. This is important because it clearly demonstrates that Vmax is neither the only nor the lowest intensity that will elicit VO\(_2\)max. This supports previous findings for cycle ergometer exercise. Poole et al. (1988) found that at intensities that were equal to and greater than critical power VO\(_2\)max was attained due to a slow component driving VO\(_2\) to VO\(_2\)max. Gaesser and Poole (1995) argue that Åstrand and Rodahl’s (1986) findings visually indicate that the VO\(_2\) did reach maximum but at the intensity above the lactate threshold there appears to be a slow component that drove VO\(_2\) to max. Second, for the purpose of this
study the attainment of \( \text{VO}_2 \text{max} \) at each intensity made it possible to compare the effect of intensity on time to achieve \( \text{VO}_2 \text{max} \) and other parameters independent of the starting and final values for \( \text{VO}_2 \). In the present study the \( \text{VO}_2 \) response for all the constant power test were described best by the mono-exponential model with a delay. The other models were unable to meet the criteria (i.e. \( R^2 \geq 0.90 \) and SEE of each parameter was \( \leq 10\% \) of parameter estimate) to be accepted as an acceptable measure of \( \text{VO}_2 \) kinetics. Also, the values for \( \tau \) from the mono-exponential model using 2 minutes of data had the same pattern as the values for \( \tau \) from the mono-exponential model using all the data. This suggested that what occurred in the first 2 minutes of exercise resembled what occurred through out the entire exercise bout. Therefore, there is no evidence of a slow component in this study.

However other studies have found different results. Barstow and Molé (1991) found evidence of a slow component for 7 of the 8 participants who exercised at intensities that required 85 and 100\% of \( \text{VO}_2 \text{max} \) for 6 minutes. Both a bi-exponential model with a delay on the second exponential response and the exponential plus linear model were used to describe the \( \text{VO}_2 \) response of these participants. They also found no significant difference in \( \tau \) between the work rates below the anaerobic threshold and those above. However there was a tendency for the \( \tau \) for the fast component to increase at the highest work rate.

The time to achieve \( \text{VO}_2 \text{max} \) in the present study was found to be participant to a linear effect of intensity \( (\rho = 0.01) \). The time to achieve \( \text{VO}_2 \text{max} \) decreased as intensity increased. This was also evident in the time that \( \text{VO}_2 \text{max} \) was sustained. The participants
reached \( \text{VO}_2\text{max} \) in 224 s at 95\% of Vmax and sustained it for 77 s, whereas at 110\% of
Vmax participants reached \( \text{VO}_2\text{max} \) faster (90 s) and sustained it for a shorter period of
time (36 s). Statistically, at the \( p \leq 0.05 \) level the time \( \text{VO}_2\text{max} \) was sustained was similar
for 100\%, 105\%, and 110\% of Vmax. \( \text{T}_{\text{lim}} \) at 100\% of Vmax (299 s) in the present study
were similar to those found by Billat et al. (1995) (321 s). Hill et al. (1997) also sought
to determine time to achieve \( \text{VO}_2\text{max} \) and how long \( \text{VO}_2\text{max} \) would be sustained. They
found that at 100\% of Vmax \( \text{VO}_2\text{max} \) was reached in 299 s and sustained for 32 s, whereas
at 92\% of Vmax it took longer to reach \( \text{VO}_2\text{max} \) and it was sustained longer (491 s at 92\%
of Vmax vs 131 s at 100\% of Vmax). The results from the present study and the one
conducted by Hill et al. (1997) suggest that exercise at a lower percentage of Vmax in a
training program would allow \( \text{VO}_2\text{max} \) to be sustained longer.

In conclusion, the results of this study demonstrate that velocity does have an effect
on the response of \( \text{VO}_2 \). During severe intensity exercise at velocities equivalent to about
95 to 110\% of Vmax, a slow component in the \( \text{VO}_2 \) response cannot be detected. In this
domain, the \( \text{VO}_2 \) response is directly related to intensity, whether the response is described
by the time constant of the exponential response or the time needed to attain \( \text{VO}_2\text{max} \). The
mechanism of this effect of intensity on kinetics cannot be deduced based on the results of
this study. Nevertheless, the influence of velocity on kinetics has implications. First the
severe intensity domain must have an upper limit. Because our participants could only
sustain 105\% and 110\% of Vmax for approximately 130 s, it may be concluded that the
upper limit is around 110\%. Secondly, that within the domain there is another threshold
(apparently below 95\% of Vmax) that must demarcate the intensity above which there is
no time for a slow component. There is evidence that at exercise above critical power a slow component drives VO\(_2\) to VO\(_2\)max. The slow component found at 92\% of Vmax by Hill et al. (1997) is the fastest intensity at which a slow component drove VO\(_2\) to VO\(_2\)max is reported. Therefore, a slow component may be responsible for the increase in VO\(_2\) to VO\(_2\)max for intensities greater than critical power (approximately 80\% of Vmax) to approximately 92\% of Vmax. However, at intensities above this range the VO\(_2\) kinetics can be described by a mono-exponential response which elicits VO\(_2\)max.
APPENDIX A

PARTICIPANT INFORMED CONSENT
UNIVERSITY OF NORTH TEXAS

DEPARTMENT OF KINESIOLOGY

CONSENT TO ACT AS A HUMAN Participant

Participant Name (print): ___________________________ Date: ______________

1) I hereby volunteer to participate as a participant in laboratory testing. I understand that this testing is part of a study entitled: "Relationship between running velocity and time to exhaustion.” The purpose of this study is to investigate the effect the response at different velocities of VO_{2}\text{max}. I understand that my participation will include eight days of testing in the Exercise Physiology Lab. I will receive a copy of this consent form. I can contact David W. Hill in his office in the Department of Kinesiology at (940) 565-2252 if I have any questions.

I hereby authorize David Hill and/or assistants selected by him to perform on me the following procedures:

a) Incremental treadmill test (VO_{2}\text{max}), to have me perform an incremental test to volitional exhaustion on a treadmill, with the work rates increased every minute until I feel that I can no longer continue, cannot maintain the required cadence, or am told to stop by the investigator; I understand that during this test my nose will be pinched shut and I will be breathing through a mouth piece;

b) Constant velocity test (anaerobic capacity), to have me run on five separate occasions to volitional exhaustion on a treadmill, the test will begin with a 6 minute warm up followed by a five minute rest then I will run to exhaustion at 95%, 100%, 105%, and 110%, of velocity of VO_{2}\text{max} (calculated from the incremental test), to obtain a 20 \mu l (2 drops) blood sample via a finger prick 5 minutes after the treadmill test.

c) Critical velocity, to have run on two separate occasions for 30 minutes on a treadmill at a submaximal speed based on the results of the previous constant velocity tests, and to obtain a 20 \mu l (2 drops) blood sample via finger prick at the fifth minute of exercise and immediately after the treadmill test.

2) The procedures outlined above have been explained to me by David W. Hill and/or assistants selected by him.

3) I understand that the procedures outlined above involve the following risks and discomforts: temporary muscle pain and soreness, possibility of abnormal changes
in my heart beat or blood pressure, or even heart attack; however, I understand that my heart rate will be monitored during testing and that I can terminate any test at any time at my discretion.

4) I have been advised that the following benefits will be derived from my participation in this study: other than learning about aerobic an strength testing and about fitness level, there are no benefits to me.

5) I understand that Dr. David W. Hill and/or appropriate assistants as may be selected by them will be selected by them will answer any inquires that I may have at any time concerning these procedures or investigation.

6) I understand that in the event of publication of the results of the study, no association will be made between the reported data and myself.

7) I understand that there is no monetary compensation for my participation in this study.

8) I understand that in the event of physical injury directly resulting from participation, compensation cannot be provided. The laboratory has an outside telephone line to the City of Denton emergency services, but a physician will not present during test.

9) I understand that I may terminate participation in this study at any time without prejudice to future care or any possible reimbursement of expenses, compensation, employment status, and that owing to the scientific nature of the study, the investigator may terminate the procedure and/or investigations at any time.

10) I understand that I may contact the chairperson of the kinesiology department’s committee on the Use of Human Participants In Research, Dr. Noreen Goggin (PEB Room 112, (940) 565-2651), on any matters concerning my participation in this study or if I feel that there is infringement on my rights.

Participant’s signature ___________________________ Date: _______________________
Witness: _______________________________ Date: ______________________
REFERENCES


Hill, D. W., Williams C. S, & Burt S. E. (1997) Responses to exercise at 92% and 100% of the velocity associated with VO\textsubscript{2max}. *International Journal of Sport Medicine, 16*, 325-329.


