THE SIGNIFICANCE OF TIME TO EXHAUSTION

AT THE VELOCITY AT VO₂MAX

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

Karen Ehler, B.A.S.

Denton, Texas

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There were two primary goals in this investigation. The first goal was to determine if inter-individual variability in time to exhaustion at the velocity associated with \( \text{VO}_2 \text{max} \) (Tlim at Vmax) was explained by anaerobic capacity (AC), Vmax, anaerobic threshold (AT), and/or a combination variable in the form

\[ AC \cdot (Vmax - vAT)' \] .

The second goal was to determine if AC could be predicted from Tlim at Vmax, AT, and/or a combination variable in the form [Tlim \cdot (Vmax - vAT)].

Participants were 17 volunteers who ran 25 km or more per week. Participants performed an incremental treadmill test for determination of \( \text{VO}_2 \text{max} \) and AT. They also performed constant velocity tests at Vmax and at different percentages of Vmax to determine Tlim and \( O_2 \) deficit. Results indicated that Tlim at Vmax is related to factors other than only AC, AT, and Vmax. Furthermore, AC is predicted by other factors than only Tlim at Vmax, Vmax, and/or AT.
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CHAPTER 1

INTRODUCTION

VO_{2}\text{max} defines the maximal rate of aerobic energy production. VO_{2}\text{max} has been found to be related to sport performance. When VO_{2}\text{max} is combined with efficiency or running economy, a “combination variable” is produced – the velocity at VO_{2}\text{max} (V_{\text{max}}). Several different methods exist to define such a combination variable. Variables derived using five of these methods have been compared (Hill & Rowell, 1995). Regardless of the method used to produce V_{\text{max}}, this “combination variable” is more useful in predicting performance than VO_{2}\text{max} (Daniels, Scardina, Hayes, & Foley, 1984).

Most of the energy for a middle distance running event is derived using the aerobic system. Depending on the definition used, V_{\text{max}} may define a velocity that mainly utilizes the aerobic system. Thus, it would make sense that V_{\text{max}} should predict an athlete’s performance. V_{\text{max}} has been reported to be the best predictor of performance in middle distance running (Lacour, Magunacelaya, Chatard, Arsac & Barthélémy, 1991). For example, Billat, Bernard, Pinoteau, Petit and Koralsztein (1994) found V_{\text{max}} to be related to performance in distances over 21 km.

Billat, Renoux, Pinoteau, Petit and Koralsztein (1995) defined V_{\text{max}} as the velocity at which VO_{2}\text{max} was first achieved in an incremental test. They have suggested that the time to exhaustion (Tlim) at one particular velocity, namely V_{\text{max}}, has special
meaning. Billat, Renoux, Pinoteau, Petit and Koralsztein (1994a; 1994b; 1995) and Billat et al. (1994) stated that this Vmax is the lowest velocity that would elicit VO$_2$max, and this, presumably, is why Tlim at Vmax was thought to have special meaning.

There has been considerable interest in evaluating the relationship between velocity (or power) and Tlim. Tlim is a function of an individual’s maximal sustainable aerobic power and his/her anaerobic capacity (AC). AC is an individual’s ability to generate short-term anaerobic energy and/or perform work using this energy. When the relationship is described by a simple hyperbolic model, maximal sustainable aerobic power is represented by critical power (CP) or critical velocity (CV). AC is represented by a parameter called AWC (i.e. “anaerobic work capacity”) (Monod & Scherrer, 1965). The relationship can be used to derive estimates of CP or CV and AWC. The following equation illustrates the relationship between velocity (v) and Tlim

$$ T_{lim} = [AWC \cdot (v - CV)^{1}] $$  (eq 1)

According to the critical power concept (equation 1), a relationship exists between velocity and Tlim. Billat et al. (1994a) rewrote this equation using vAT (the velocity at AT) in place of CV, AC in place of AWC, and Vmax in place of v. AT represents the exercise level in which blood lactate begins to increase systematically above a resting baseline level (McArdle, Katch & Katch, 1991). For exercise at Vmax, the equation was

$$ T_{lim \ at \ V_{max}} = [ AC \cdot (V_{max} - v_{AT})^{1}] $$  (eq 2)

Although Vmax may be similar in a group of subjects, there is still inter-individual variability in Tlim at Vmax. Theoretically, this variability is explained completely by
anaerobic threshold (AT) and anaerobic capacity (AC). Hill and Rowell (1996) reported that not all variability in Tlim at Vmax could be explained by AT and AC. They found that no more than 26% of the variability in Tlim at Vmax was explained by AC. The VAT explained only 44% of the variability in Tlim at Vmax, and only 36% of the variability in Tlim at Vmax was explained by the combination variable. By rearranging the equation, AC should be predicted by Tlim at Vmax, AT, or a combination variable as illustrated in the equation

$$AC = [Tlim \cdot (Vmax - vAT)]$$  (eq 3).

Renoux, Billat, Pinoteau, Petit and Koralsztein (in press) determined AC from time to exhaustion at 120% of Vmax. Results indicated a significant positive correlation between values for Tlim at 100% of Vmax and Tlim at 120% of Vmax. This suggested that AC played a role in the ability to sustain Vmax. Hill and Rowell reported that only 26% of the variance in O2 deficit was explained by Tlim at Vmax. Only 45% of the variance in O2 deficit could be explained by the combination variable. While these authors concluded that differences in AC and AT did not completely explain differences in Tlim at Vmax, they did note several shortcomings in their methods.

Purpose

The first goal of this investigation was to determine if inter-individual variability in Tlim at Vmax was explained by AC, Vmax, AT, and/or a combination variable in the form $[AC \cdot (Vmax - vAT)^1]$. O2 deficit was the criterion measure of AC in this investigation. The second goal was to determine if AC could be predicted from Tlim at Vmax, Vmax, AT, and/or a combination variable in the form $[Tlim \cdot (Vmax \cdot vAT)]$. If
AC could, in fact, be predicted by the combination variable, this would mean that only two tests (one incremental test and one constant velocity test) would be necessary to obtain an estimate of AC.

Hypotheses

The first hypothesis of this study was that Tlim at Vmax would be significantly correlated with AC, Vmax, and/or AT. The second hypothesis was that Tlim at Vmax would be significantly correlated with the combination variable \( (AC \cdot (Vmax - vAT)^{-1}) \). The third hypothesis was that AC would be significantly correlated with Tlim at Vmax, Vmax, and/or AT. Finally, the fourth hypothesis was that AC would be significantly correlated with a combination variable in the form \( [Tlim \cdot (Vmax - vAT)] \).

Delimitations

This investigation was delimited in the following ways:

1. Participants were volunteers who ran 25 km or more per week.
2. Participants ranged in age from 18 to 43 years.
3. Participants performed six treadmill tests – one incremental and five constant power tests. \( O_2 \) deficit was determined using modifications of methods by Medbo, Mohn, Tabata, Bahr, Vaage, and Sejersted (1988) and Hill (1996).

Limitations

1. Because the investigation was limited to participants who ran 25 km or more per week, results may not be generalizable to all populations.
2. Runners may not have given full effort during all tests.
3. AT was used in place of critical power. The two are related but not synonymous.

4. The precision of attaining Vmax and vAT was limited to the increments used in the incremental test. This low precision may have had a negative effect on the ability to determine the relationship between variables.

5. Tlim at Vmax is not a very reliable measure. It is difficult to obtain valid estimates of anaerobic capacity or factors that determine Tlim at Vmax if a single measure of Tlim at Vmax is not determined with a high degree of reliability.

6. $O_2$ demand was extrapolated from the results of only four 6-min submaximal bouts which may have lead to invalid estimates of $O_2$ deficit.

7. $O_2$ deficit is not a very reliable measure. It is difficult, therefore, to obtain valid estimates of anaerobic capacity or the factors that determine Tlim at Vmax if the measure of anaerobic capacity is not determined with a high degree of reliability.

Significance of Investigation

It has been suggested that Tlim at Vmax provides a "meaningful parameter" for monitoring distance runners (Billat, et al., 1994a, 1994b, 1995; Billat, et al., 1994). Yet, the meaning of Tlim at Vmax is not clear. It would be meaningful if the factors that determine Tlim at Vmax were elucidated.

It would also be meaningful if there were found to be a strong relationship between AC and the combination variable in the form $[Tlim \cdot (Vmax - vAT)]$. This
would mean that AC could be determined based only on the results of two tests: one incremental test and one test at Vmax. This would be more practical than the 10 to 20 submaximal tests and one all-out test (Medbo, et al., 1988) or the several all-out tests (Hill, 1996) that are presently required to determine AC.
CHAPTER II

REVIEW OF LITERATURE

The purpose of this investigation was to evaluate if and how AC, Vmax, AT and/or a combination variable explained inter-individual variability in Tlim at Vmax.

The second purpose of this investigation was to determine if AC could be estimated from Tlim at Vmax, Vmax, AT and/or a combination variable.

Participants were volunteers who ran 25 km or more per week. Participants performed an incremental treadmill test for determination of VO$_2$max, AT, and Vmax. Constant power tests on a treadmill were also performed by participants to calculate their O$_2$ deficit, the criterion measure of AC. In this chapter, discussion focused on previous investigations which have dealt with different methods of determining Vmax, and investigations which specifically addressed Tlim at Vmax and its relationship with AT, AC, and Vmax.

Methods of Determining Vmax

Vmax can be defined using one of several definitions. Vmax may be defined as the velocity at which VO$_2$max is first elicited using a progressive exercise protocol on a treadmill (Billat, et al., 1994; Billat, et al., 1994a, 1994b, 1995). Vmax may also be determined by extrapolation of the velocity:VO$_2$ relationship (Cunningham, 1990; Daniels, et al., 1984; Morgan, Baldini, Martin, & Kohrt, 1989). di Prampero (1986) calculated Vmax from VO$_2$max and running economy. Furthermore, Vmax can be
calculated from VO_{2max} and running economy, making a correction for resting VO_{2} (Lacour, et al., 1991). Finally, Vmax may be defined as the highest treadmill velocity that can be sustained for 1 min in an incremental test (Noakes, Myburgh, & Schall, 1990; Scrimgeour, Noakes, Adams, & Myburgh, 1986). Vmax, as defined by Daniels et al., Billat, Renoux et al., Billat, Bernard et al., and Noakes et al., should involve an anaerobic component because each represents a velocity above the anaerobic threshold. Vmax as defined by di Prampero and Lacour et al. represents a running velocity that could be sustained aerobically, if there were no anaerobic contribution. Although these definitions are often used interchangeably, five different parameters are being described (Hill & Rowell, 1995). In order to maintain consistency throughout this entire paper, the velocity associated with VO_{2max} will be called Vmax, regardless of what method or abbreviation other authors might have used in their investigations.

**Physiological Significance of Tlim at Vmax**

Previous investigations have evaluated the possible relationship among Tlim at Vmax and performance, AC, Vmax and AT. The following sections will briefly review these investigations and provide insight into the relationship between Tlim at Vmax and these factors.

**Is Tlim at Vmax a reliable measure?**

In runners, the mean value for Tlim at Vmax may be consistent from one week to the next. However, Tlim at Vmax may not be consistent in individual runners over the same period of time (Billat, et al., 1994b). Woodward, Williams, Goggin, and Hill (1998) reported that Tlim was a reliable measure, but a learning effect occurred from the
first test to the second. If \( T_{\text{lim}} \) at \( V_{\text{max}} \) is not a reliable measure, it is difficult to determine relationships between it and factors that determine \( T_{\text{lim}} \) at \( V_{\text{max}} \).

Billat et al. (1994b) assessed the reproducibility of \( T_{\text{lim}} \) at \( V_{\text{max}} \) and examined the relationship between \( T_{\text{lim}} \) at \( V_{\text{max}} \) and other bioenergetic characteristics. Eight sub-elite male runners performed the exercise tests. Participants first performed a progressive treadmill test to determine \( V_{O_2\text{max}}, V_{\text{max}}, \) and lactate threshold. \( V_{\text{max}} \) was defined as the lowest treadmill velocity that elicited a \( V_{O_2} \) equal to \( V_{O_2\text{max}} \). On a separate occasion, and following a 20-min warm-up at 60% \( V_{\text{max}} \), treadmill velocity was increased to \( V_{\text{max}} \) and participants were encouraged to run to exhaustion. Participants performed two of these constant power tests which were separated by a 1-wk interval. Mean exercise times to exhaustion were not significantly different on the first and second test (6 min 44 s vs 6 min 42 s). This suggested that mean \( T_{\text{lim}} \) at \( V_{\text{max}} \) was reproducible in a group of sub-elite runners at a 1-wk interval. However, large differences were found between the individual results on the two tests, despite the fact that the mean value of \( T_{\text{lim}} \) at \( V_{\text{max}} \) across all runners was very close.

Woodward et al. (1998) evaluated the reproducibility of responses to high intensity treadmill tests. Participants included 35 volunteers (21 women and 14 men). Each participant performed two constant velocity test on two separate days at an average velocity of 277 m·min\(^{-1}\). Expired gases were collected during each test to determine \( V_{O_2\text{max}} \) and maximal RER. \( T_{\text{lim}} \) was also measured to the nearest second for each test. Results found that \( T_{\text{lim}} \) was a reliable measure. However, there was a practice effect that
occurred. Tlim increased 12% from the first test to the second test. They concluded that a single test is not sufficient when measuring an important variable such as Tlim.

Billat et al. (1994b) reported that Tlim at Vmax could be a reliable measure when looking at group means. However, large inter-individual differences on the two tests indicated that Tlim at Vmax may not be reliable when monitoring individual athletes. Woodward et al. (1998) found that Tlim was a reliable measure despite the fact that there was a learning effect from the first test to the next. If Tlim at Vmax is not a reliable measure, it is difficult to obtain valid estimates of the factors that determine Tlim at Vmax.

Is Tlim at Vmax related to performance?

Vmax has been reported as the best predictor of performance in middle distance running (Billat, et al., 1994; Lacour, et al., 1991). It has been demonstrated in several investigations that Tlim at Vmax was related to performance (Billat, Beillot, Jan, Rochcongar & Carre, 1996; Billat, et al. 1994b).

In a study by Billat et al. (1994), VO₂max and Vmax were determined using a progressive exercise protocol on a treadmill. Ten sub-elite, male, long distance runners performed three tests over a 1-wk interval. All subjects had similar average velocities for half-marathon races. The first test was a progressive exercise test on a treadmill to determine VO₂max and Vmax. The initial speed was set at 12 km·h⁻¹ and was increased 2 km·h⁻¹ every 3 min until the runner reached 80% of his best performance in a 3000 m run. Velocity was increased by only 1 km·h⁻¹ for each subsequent stage. VO₂max was determined by a plateau in VO₂ despite an increase in velocity, a respiratory exchange
ratio above 1.1, or a heart rate above 90% of the participant’s predicted maximal heart rate. \( V_{\text{max}} \) was defined as the lowest treadmill speed which elicited a \( VO_2 \) equal to \( VO_2_{\text{max}} \). \( T_{\text{lim}} \) at \( V_{\text{max}} \) was related to performance in the half-marathon when race velocity was expressed as a percentage of \( V_{\text{max}} \) (\( r = 0.604 \)). However, \( T_{\text{lim}} \) at \( V_{\text{max}} \) was not related to actual race velocity (\( r = 0.27 \)). The authors concluded that \( V_{\text{max}} \) is the best predictor of performance over 21 km in sub-elite, male, long distance runners.

Lacour et al. (1991) compared \( V_{\text{max}} \) calculated from treadmill measurements to \( V_{\text{max}} \) obtained with the Université de Montreal Track-Test. These values were then related to the velocities sustained during a middle-distance running event. Participants were thirty-two athletes of mean age 23.2 years. All participants were experienced runners who competed in distances ranging from 800m to marathon. Participants performed an intermittent graded treadmill test in order to obtain \( VO_2_{\text{max}} \). Running durations were 4 min and rest periods were 1 min. Initial velocity was 10.3 \( \text{km} \cdot \text{h}^{-1} \) and was increased by 1.54 \( \text{km} \cdot \text{h}^{-1} \) after each rest period until the runner reached exhaustion. The \( VO_2 \) measurement during the last stage of running was considered maximal if blood lactate concentration was higher than 9 \( \text{mmol} \cdot \text{l}^{-1} \). The energy cost of running (MR) was also calculated as follows:

\[
\text{MR} = (VO_2 - 0.083) \cdot v^{-1}.
\]

\( V_{\text{max}} \) was then calculated as:

\[
V_{\text{max}} = (VO_2_{\text{max}} - 0.083) \cdot \text{MR}^{-1}.
\]

Participants also performed the UMTT within the week either preceding or following measurement of \( V_{\text{max}} \). Results indicated that \( V_{\text{max}} \) obtained from the UMTT was
slightly higher than Vmax measured on a treadmill. However, the two velocities were highly correlated \((r = 0.92, p < 0.001)\). Results also indicated that Vmax was related to performance because velocities sustained at 1500m were correlated with Vmax values from the UMTT and the treadmill \((r = 0.91 \text{ and } 0.90, p < 0.001)\). It was concluded that either the UMTT or treadmill could be used to obtain Vmax. Both methods provide similar values and can be used in monitoring athlete's training.

An investigation by Billat et al. (1996) studied the influence of gender on \(T_{lim}\) at Vmax and 1500 m track performance. Participants in the study were 29 elite middle-distance runners. There were 14 women and 15 men. Three treadmill tests were performed over a 2-wk period. A slope of 3\% was used for all tests. An intermittent graded exercise test was performed for determination of VO\(_2\)\text{max}. Running durations and rest periods were 4 and 1 min, respectively. Initial speed was set at 12 km·h\(^{-1}\) for the men and 10 km·h\(^{-1}\) for the women. Speed was increased by 2 km·h\(^{-1}\) for each stage. The increment was only 1 km·h\(^{-1}\) for the last stage. Criteria for accepting VO\(_2\)\text{max} were exhaustion of the subject, a leveling off of VO\(_2\) despite an increase in velocity, an RER greater than 1.1 or a blood lactate concentration higher than 8.5 mmol·l\(^{-1}\). Vmax was calculated according to the equation of di Prampero (1986) in the form

\[
V_{\text{max}} = (V_{\text{O2 max}} - V_{\text{O2 rest}}) \cdot CR,
\]

where CR (ml O\(_2\)·kg\(^{-1}\)·m\(^{-1}\)) is the oxygen cost of running per unit of body mass at a given velocity. The second test session consisted of a 15-min warm-up at 60\% of Vmax. Then treadmill speed was quickly increased to Vmax. Subjects were encouraged to run to exhaustion. \(T_{lim}\) at Vmax was determined. The last test was a run to exhaustion at
110% of Vmax in order to determine the subject's accumulated O\textsubscript{2} deficit, the criterion measure for anaerobic capacity. Subjects performed a run to exhaustion at 110% of Vmax. The test was preceded by a 15-min warm-up at 60% of Vmax. Tlim at Vmax did not differ between the male and female groups of runners. Tlim at Vmax was related to performance in the male runners, but not the female runners. Therefore, it was concluded that Tlim at Vmax was related to 1500 m track performance in male runners, and Tlim at Vmax does not differ between genders at different performance speeds.

Billat et al. (1994b) also looked at the relationship between Tlim at Vmax and half-marathon performance. Participant characteristics and methods were described earlier on page 9 of this thesis. The authors reported a significant correlation between Tlim at Vmax and the speed over 21.1 km (in km·h\textsuperscript{-1}) (r = 0.72, p < .05). They concluded that subjects who were capable of sustaining their Vmax for a longer period of time were also those who ran a 21.1 km race faster.

Tlim at Vmax is related to performance in middle distance running. Similar values of Tlim at Vmax can be obtained from either treadmill or field testing and then used to predict performance. Gender has no effect on Tlim at Vmax, and Tlim at Vmax has been found useful in predicting performance in male runners. Finally, Tlim at Vmax is related to performance. Although a relationship exists between Tlim at Vmax and performance, past research has not been totally consistent or conclusive in describing this relationship.
Is Tlim at Vmax related to AT and AC?

Based on the relationship between the physiological factors presented in equation 2, Tlim at Vmax should be related to AT and AC. Four studies (Billat, et al., 1994a; Billat, et al., 1995; Hill & Rowell, 1996; Renoux, et al., in press) investigated the relationships between Tlim at Vmax and AC, Tlim at Vmax, and AT. Lactate threshold (LT) is one specific way to determine what is broadly called AT and will be mentioned in several investigations.

Billat et al. (1994a) measured Tlim at Vmax on a treadmill in 38, elite, male, long-distance runners. A progressive exercise protocol was used to measure VO$_2$max, Vmax and LT for each subject. Initial speed was set at 12 km·h$^{-1}$ (0% slope) and was increased by 2 km·h$^{-1}$ every 3 min up to 80% of the runner’s speed in a 1.5 km race and 1 km·h$^{-1}$ thereafter. Lactate concentrations were analyzed from a fingertip blood sample that was obtained during the last 30s of each stage. One week later, runners performed a test at 100% of Vmax, and they were encouraged to run to exhaustion. Tlim at Vmax was measured. Criteria for determining VO$_2$max were a plateau in VO$_2$ despite an increase in running speed, an RER above 1.1, or a heart rate over 90% of the predicted maximal heart rate. Vmax was defined as the lowest velocity that elicited a VO$_2$ equal to VO$_2$max. LT was defined as a point of accelerated lactate accumulation around 4 mM. Lactate concentration was expressed in % VO$_2$max. The mean value for LT was 197 ml·kg$^{-1}$·km$^{-1}$. Tlim at Vmax was positively correlated with LT ($r = 0.378$, $p < 0.05$).

Billat et al. (1995) examined the relationship between Tlim at Vmax and AC. Participants were 14, elite, male, long distance runners. In order to obtain measurements
of \( \text{VO}_2 \text{max} \), \( \text{Vmax} \), and lactate threshold, participants were tested using a progressive exercise protocol on a treadmill. Velocity was initially set at 12 km\( \cdot \)h\(^{-1} \) with a 0% slope. Velocity was increased by 2 km\( \cdot \)h\(^{-1} \) every 3 min until the runners reached 80% of their velocity in a 1.5 km race. After that point, velocity was increased by only 1 km\( \cdot \)h\(^{-1} \) every 3 min. Over three different sessions, which were separated by 1 wk, participants were tested at 90%, 100%, and 105% of \( \text{Vmax} \). Each test was preceded by a 15-min warm-up at 60% \( \text{Vmax} \). Following the warm-up, velocity was quickly increased to 90%, 100%, or 105% of \( \text{Vmax} \). Participants ran to exhaustion. AC was calculated from \( \text{Tlim} \) at 90%, 100%, and 105% of \( \text{Vmax} \). The criterion measure for AC was the y-intercept of the line representing the relationship between running distance and \( \text{Tlim} \). This parameter which they called ARC (i.e. “anaerobic running capacity”) is the equivalent of AWC when the mode is running. Results demonstrated that the correlation between \( \text{Tlim} \) at \( \text{Vmax} \) and AC was 0.42. They were not significantly correlated. There were also no significant correlations between LT and \( \text{Tlim} \) at \( \text{Vmax} \), when LT was expressed as a % of \( \text{Vmax} \) or a % of \( \text{VO}_2 \text{max} \) (0.30 and 0.16, respectively).

Hill and Rowell (1996) investigated a possible relationship between \( \text{Tlim} \) at \( \text{Vmax} \) and AT or AC. Participants for the study were 13 members of a university women’s track team. AT, \( \text{VO}_2 \text{max} \), and \( \text{Vmax} \) were determined from an incremental treadmill test with a 0% slope. The test began with three 5-min stages. Each stage was followed by a 5 min rest. The following stages were of 2 min duration, and they were performed with no rest periods. The increments were 0.5 miles \( \cdot \) h\(^{-1} \). Following this test and on a different day, participants each performed a test at \( \text{Vmax} \). The test consisted of three 5-min stages that
were each followed by a 5-min rest. Following the warm-ups, treadmill velocity was increased to the subject’s Vmax. Participants ran to exhaustion. O2 deficit and Tlim at Vmax were determined from this constant velocity test. vAT2 was identified by a second breakaway in Ve, an increase in Ve/VCO2, and an initial decrease in % CO2 in the expired air, plotted against time and/or VO2. Results indicated that no more than 26% of the variability in Tlim at Vmax was explained by differences in AC, with O2 deficit being the criterion measure of AC; 44% was explained by the velocity at AT2 (vAT2). Finally, 36% of the variability in Tlim at Vmax was explained by the combination variable [O2 deficit · (Vmax - vAT2)].

Renoux et al. (in press) compared physiologic responses during exhaustive treadmill runs at 100% and 120% of Vmax. The purpose was to see if inter-individual variability in Tlim at Vmax was due to differences in participants’ AC. Fourteen, sub-elite male runners performed three exercise tests on a treadmill. To determine Vmax and VO2max, a continuous incremental protocol was used. Initial velocity was set at 12 km·h−1 with a 0% slope. Velocity was increased every 3 min by 2 km·h−1 up to the subject’s running velocity in a 3 km race. Velocity was then increased by 1 km·h−1 every 3 min thereafter. Participants were instructed to run until exhaustion. Criteria for determining VO2max were a plateau in despite an increase in running speed, an RER above 1.1, or a heart rate over 90% of the predicted maximal heart rate. Vmax was defined as the lowest treadmill velocity which elicited VO2max. A fingertip blood sample was obtained and analyzed for lactate concentration during the last 30 s of each stage. In order to determine Tlim at 100% and 120% of Vmax, two constant velocity tests were performed by the
subjects. Both tests began with a 15-min warm-up at 60% V\textsubscript{max}. Then treadmill velocity was increased to V\textsubscript{max} or 120% of V\textsubscript{max} and subjects ran to exhaustion. AC was determined from time to exhaustion at 120% of V\textsubscript{max}. Neither T\textsubscript{lim} at 100% nor 120% was significantly correlated with blood lactate from the two tests (r = 0.51, p = 0.06 and r = 0.47, p = 0.09, respectively. A positive correlation (r = 0.52) resulted between T\textsubscript{lim} at 100% and AC. The correlation was not significant. Perhaps there is some evidence that a relationship exists between T\textsubscript{lim} at V\textsubscript{max} and AT and between T\textsubscript{lim} at V\textsubscript{max} and AC. However, past studies have shown that there is not always a significant relationship between these physiological factors. Clearly, neither AT nor AC completely explains variance in T\textsubscript{lim} at V\textsubscript{max}. Other factors have an influence on the variability in T\textsubscript{lim} at V\textsubscript{max}.

Is T\textsubscript{lim} at V\textsubscript{max} related to VO\textsubscript{2}\textsubscript{max} or V\textsubscript{max}?

In a recent review, Billat and Koralsztein (1996) stated that T\textsubscript{lim} at V\textsubscript{max} was negatively related to V\textsubscript{max} and VO\textsubscript{2}\textsubscript{max}. They cited their own study (Billat, et al., 1994a) in which they found that participants who had the highest values of T\textsubscript{lim} were also those who had the highest velocity associated with the LT value. LT was expressed as a fraction of V\textsubscript{max}. Participants who had the highest values of T\textsubscript{lim} also had the lowest values of V\textsubscript{max}. Findings from this study were in accordance with Monod and Scherrer's (1965) model (see equation 1). It makes sense, however, that T\textsubscript{lim} at V\textsubscript{max} values should be similar for all participants when they are running at the same relative velocity calculated as a percentage of V\textsubscript{max} or VO\textsubscript{2}\textsubscript{max}. Despite the statement by Billat and Koralsztein that T\textsubscript{lim} is negatively correlated with VO\textsubscript{2}\textsubscript{max} and V\textsubscript{max}, a review of
the literature reveals that only four studies reported negative correlations between Tlim at Vmax and Vmax (Billat, et al., 1994; Billat, et al., 1994a, 1995; Renoux, et al., in press). Billat et al. (1994a, 1995) also reported a negative correlation between Tlim at Vmax and VO₂max. Two studies resulted in positive correlations between Tlim at Vmax and Vmax and between Tlim at Vmax and VO₂max (Billat, et al., 1994b; Hill & Rowell, 1996). Results of these studies are summarized in Table 1.

In the study by Billat, et al. (1994), the significance of Vmax and Tlim at Vmax was evaluated. Methods employed for the investigation and participant characteristics were described previously on pages 10 and 11 of this thesis. Subjects were ten, sub-elite, male, long-distance runners. There was no relationship between Tlim at Vmax and VO₂max (r = 0.016) and a negative relationship (r = -0.314) resulted between Tlim at Vmax and Vmax.

Billat et al. (1994a) examined the relationship between Tlim at Vmax and VO₂max and between Tlim at Vmax and Vmax. Participant characteristics and methods were described in more detail on page 14 of this thesis. The number of subjects in this study was 38. There was a negative correlation between Tlim at Vmax and Vmax (r = -0.362; p < 0.05). A negative correlation was also found between Tlim at Vmax and VO₂max (r = -0.347; p < 0.05).

Billat et al. (1995) reported a negative correlation between Tlim at Vmax and VO₂max (r = -0.20) and between Tlim at Vmax and Vmax (r = -0.54, p < 0.05) in fourteen, elite, male, long-distance runners. Participant characteristics and methods were discussed in more detail on pages 14 and 15 of this thesis.
Renoux et al. (in press) compared physiological responses during treadmill runs performed at 100% of $V_{max}$. They explored the possibility of inter-subject variability in $T_{lim}$ at $V_{max}$ in fourteen, sub-elite, male runners who were homogenous with respect to $VO_{2_{max}}$. Participant characteristics and methods were discussed on pages 16 and 17 of this thesis. Results indicated a negative correlation ($r = -0.50$) between $T_{lim}$ at $V_{max}$ and $V_{max}$. The correlation was not significant. The correlations between $T_{lim}$ at $V_{max}$ and $VO_{2_{max}}$ were not reported.

Billat et al. (1994b) conducted a study with eight, sub-elite male runners. Once again, participant characteristics and the methods employed for the investigation were described previously on page 9 of this thesis. There was no relationship between $T_{lim}$ at $V_{max}$ and $VO_{2_{max}}$ ($r = 0.138$). No significant relationship was revealed between $T_{lim}$ at $V_{max}$ and $V_{max}$ ($r = 0.241$).

Hill and Rowell (1996) found no significant correlation ($p = 0.34$) between $T_{lim}$ at $V_{max}$ and $V_{max}$ in thirteen members of a university women’s track team. Participant characteristics and methods were described earlier on pages 15 and 16 of this thesis. No more than 12% of the variability in $T_{lim}$ at $V_{max}$ was explained by $V_{max}$. A positive correlation ($r = 0.76$) was found between $T_{lim}$ at $V_{max}$ and $VO_{2_{max}}$.

### Table I. Correlations between $T_{lim}$ at $V_{max}$ and $V_{max}$ and between $T_{lim}$ at $V_{max}$ and $VO_{2_{max}}$

<table>
<thead>
<tr>
<th></th>
<th>$V_{max}$ (km·h(^{-1}))</th>
<th>$VO_{2_{max}}$ (ml·kg(^{-1})·min(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Billat, et al. (1994a)</td>
<td>-0.362</td>
<td>-0.347</td>
</tr>
<tr>
<td></td>
<td>$p &lt; 0.05$</td>
<td>$p &lt; 0.05$</td>
</tr>
<tr>
<td>Billat, et al. (1994b)</td>
<td>0.241</td>
<td>0.138</td>
</tr>
<tr>
<td></td>
<td>$p = 0.57$</td>
<td>$p = 0.74$</td>
</tr>
</tbody>
</table>
Billat, et al. (1994) 
-0.314  0.016

-0.54  -0.20  
p < .05

Renoux, et al. (in press) 
-0.50  0.66  
p = .07  p = 0.01

Hill & Rowell (1996) 
0.34  0.76  
p = 0.34  p < .05

Despite Billat and Koralsztein's (1996) assertion that Tlim at Vmax is inversely related to Vmax and VO₂max, several of the previous studies reflect no relationship between Tlim at Vmax and Vmax or between Tlim at Vmax and VO₂max. The negative correlations between Tlim at Vmax and Vmax could be explained by an overestimation of Vmax. The runners with higher values of Vmax might have actually been running at velocities greater than 100% of Vmax.

Is Tlim at Vmax related to a combination variable?

Based on the critical power concept (equation 1), it makes sense that Tlim at Vmax should be related to a combination variable. Three studies (Billat, et al., 1994a; Hill & Rowell, 1996; Renoux, et al., in press) investigated the relationship between Tlim at Vmax and a combination variable.

Billat et al. (1994a) measured Tlim at Vmax on a treadmill in 38, elite, male, long-distance runners. Participant characteristics and methods employed were discussed earlier on page 14 of this thesis. Results indicated a negative relationship between Tlim at Vmax and Vmax (r = -0.362, p < 0.05) and between Tlim at Vmax and
VO₂ max (r = -0.347, p < 0.05). They concluded that runners who obtained the highest values for Vmax were also those who reached exhaustion in a shorter amount of time. Their findings were in accordance with those by the model of Monod and Scherrer (1965). This model suggests that the highest values of Tlim at Vmax should be obtained with a high AC and a low value of the difference between Vmax and the fraction of VO₂ max at the LT. Their findings reflected the relationship predicted by Monod and Scherrer (1965). These authors concluded that there should be a relationship between Tlim at Vmax and the combination variable since a relationship was found between Tlim at Vmax and Vmax and Tlim at Vmax and VO₂ max.

Hill and Rowell (1996) examined the relationship between Tlim at Vmax and a combination variable. One of the purposes of their study was to identify whether inter-individual differences in Tlim at Vmax were explained by differences in the combination variable inspired by the critical power concept. Participant characteristics and methods for the study were described earlier on pages 15 and 16 of this thesis. The authors also investigated the possibility of predicting AC from the combination variable. They found that 36% of the variability in Tlim at Vmax was explained by \[O₂ \text{ deficit} \cdot (Vmax - vAT2)^4\]. Only 45% of the variance in O₂ deficit could be explained by the combination variable \[Tlim \cdot (100\% - \%VO₂ \text{ max at AT2})\]. They concluded that most of the variability in Tlim at Vmax was not explained by the variables evaluated in their study, and AC could only be crudely estimated by the combination variable.

The purpose of a study by Renoux et al. (in press) was to see if inter-individual variability in Tlim at Vmax was due to differences in AC. The study was performed with
14, sub-elite, male runners. Subject characteristics and methods employed in the study were discussed earlier on pages 16 and 17 of this thesis. Results indicated that Tlim at Vmax was positively correlated with AC, but the correlation just failed to achieve statistical significance ($r = 0.52, p = 0.06$). Their findings were also in accordance with the model by Monod and Scherrer (1965). Therefore, the authors concluded that there should be a relationship between Tlim at Vmax and a combination variable.

Tlim at Vmax should be related to a combination variable inspired by the critical power concept. However, Hill and Rowell (1996) could only contribute 36% of the variability in Tlim at Vmax to the combination variable. Billat et al. (1994a) and Renoux et al. (in press) stated that the inverse relationship between Tlim at Vmax and Vmax and between Tlim at Vmax and VO$_2$max was in accordance with the model by Monod and Scherrer (1965). Renoux et al. (in press) found no relationship between Tlim at Vmax and AC. Theoretically, Tlim at Vmax should be related to a combination variable, but past research has not reported strong enough findings to support this concept.

Determination of Anaerobic Capacity

If a relationship does, in fact, exist between Tlim at Vmax and AT, AC and a combination variable, it seems to follow that AC should be predicted from Tlim at Vmax, Vmax, AT and/or a combination variable. Several investigations have explored this possibility. The following section will review these investigations and provide previous findings regarding the relationship between AC and these physiological factors.
Is AC explained by Tlim at Vmax and AT?

Theoretically, AC should be explained by Tlim at Vmax and AT (equation 3). Three investigations (Billat, et al. 1995; Hill & Rowell, 1996; Renoux, et al., in press) examined the possible existence of this relationship to discover if AC could, in fact, be predicted from Tlim at Vmax and AT.

Billat et al. (1995) conducted a study with fourteen, elite, male, long-distance runners. Participant characteristics and methods used in the investigation were discussed earlier on page 14 and 15 of this thesis. They examined the relationship between AC and Tlim at three relative intensities (90%, 100%, and 105% of Vmax) and AC. AC was determined as the y-intercept of the relationship between running distance and Tlim. AC was calculated from Tlim at 90%, 100%, and 105% of Vmax obtained on a treadmill. LT was defined as the VO₂ corresponding to a marked acceleration in the lactate curve around 3.5 mM. Results indicated a nonsignificant relationship (r = 0.42) between Tlim at Vmax and AC. There was a significant relationship between Tlim at 105% of Vmax and AC. There was also a significant relationship (r = 0.54, p < 0.05) between Tlim at 90% of Vmax and LT, when LT was expressed as a percentage of Vmax. However, no significant relationship was observed between Tlim at 100% of Vmax and LT (r = 0.30), when LT was expressed as a percentage of Vmax. Although AC was related to Tlim at Vmax, it must be understood that AC was calculated directly from Tlim at Vmax.

Results from the study by Hill and Rowell (1996) indicated that only 26% of the variance in O₂ deficit was explained by Tlim at Vmax. Only 45% of the variance could be explained by the compound variable \[ T \text{lim} \cdot (Vmax - \%VO₂ \text{max at AT2}) \]. The
correlation between $O_2$ deficit and Tlim at Vmax was 0.51 ($p < 0.05$). The highest correlation between $O_2$ deficit and any form of the compound variable was 0.67 ($p < 0.01$). In this study by Hill and Rowell, AC could not be predicted from the combination of Tlim and AT. The authors provided several possible reasons for this. First of all, AT was used in place of critical power. The two are related but are not exactly the same (Hill, 1993). This might partly account for the failure to predict AC. Also, $O_2$ deficit is not a very reliable measure of AC (Green & Dawson, 1993), and only six 5-min submaximal bouts were used to extrapolate $O_2$ demand. A third reason that might account for the failure to predict AC from the compound variable is that Tlim at Vmax is not a very reliable measure when evaluating inter-individual differences (Billat, et al., 1994b). Furthermore, the increments used in the incremental test limited the precision in which AT and Vmax were attained. Finally, lack of motivation could have negatively influenced only some of the measures.

It was hypothesized by Renoux et al. (in press) that the large inter-subject variability in Tlim at Vmax was due to differences in AC. Fourteen, subelite, male runners were subjects in the investigation. The data collected during an exhaustive run at 120% of Vmax was used to determine AC. Participant characteristics and methods were discussed earlier on pages 16 and 17 of this thesis. Values for Tlim at 100% and Tlim at 120% of Vmax were not significantly correlated ($r = 0.52$, $p = 0.06$). Tlim at 120% of Vmax may not be a valid measure of AC, and this may partly account for the inability to find a significant relationship between Tlim at Vmax and AC.
Very few significant relationships were observed between AC and Tlim at Vmax, AT and/or a combination variable in the investigations previously discussed. According to equation 3, however, AC should be predicted completely by these factors. Other factors must also predict AC and contribute to its measure or there were problems in obtaining valid measures of AC, Tlim at Vmax and AT in these studies.

Summary

Vmax is a combination variable that combines VO$_2$max with efficiency or running economy. Vmax may be derived using any one of several definitions. The definition used determines the value which will be obtained in a study (Hill & Rowell, 1995). These authors found large intra-individual differences in values obtained using different definitions of Vmax.

An equation adapted from that proposed by Monod and Scherrer (1965) illustrates the relationship between velocity and Tlim (see equation 1). The relationship can be used to derive estimates of CV and AWC. The Tlim at one particular velocity, namely Vmax, is said to have special meaning (Billat, et al., 1995). Tlim at Vmax was found to be a reliable measure in a group of sub-elite runners tested at a 1-wk interval but was not a reliable measure when looking at inter-individual differences (Billat, et al., 1994b). Tlim at Vmax is thought to have physiological significance when predicting an athlete's performance, and this relationship has been investigated in the past (Billat, et al., 1995; Billat, et al., 1994; Billat, et al., 1994b; Lacour, et al., 1991). A relationship between Tlim at Vmax, AC, Vmax, and AT has also been investigated in the past.
Based on the relationship illustrated in equation 2, Tlim at Vmax should be related to AT, AC, Vmax, and/or VO$_{2\text{max}}$. Several investigations evaluated this relationship. Two studies reported positive correlations between Tlim at Vmax and Vmax (Billat, et al., 1994b; Hill & Rowell, 1996). Four studies reported negative correlations between Tlim at Vmax and Vmax (Billat, et al., 1994; Billat, et al., 1994a; Billat, et al., 1995; Renoux, et al., in press). Two of these studies reported significant correlations (Billat, et al., 1994a; 1995). Two significant, positive correlations have been reported between Tlim at Vmax and AT (Billat, et al., 1994a; Hill & Rowell, 1996). Billat et al. (1995) reported a positive correlation between Tlim at Vmax and AT. Two investigations reported no correlation between Tlim at Vmax and VO$_{2\text{max}}$ (Billat, et al., 1994; Billat, et al., 1994b). Billat et al. (1995) and Billat et al. (1994a) reported negative correlations between Tlim at Vmax and VO$_{2\text{max}}$, with the latter being a significant correlation. The only positive correlation found between Tlim at Vmax and VO$_{2\text{max}}$ was in an investigation by Hill and Rowell (1996). A significant, positive correlation was found between Tlim at Vmax and AC in one investigation (Hill & Rowell, 1996). Renoux et al. (in press) reported a positive correlation between Tlim at Vmax and AC. Billat et al. (1995) also reported a positive correlation between Tlim at Vmax and AC, but the relationship failed to reach statistical significance. Past research has indicated either no relationship or a negative relationship between Tlim at Vmax and Vmax and between Tlim at Vmax and VO$_{2\text{max}}$ in the majority of relationships evaluated. There is stronger evidence of a positive relationship between Tlim at Vmax and AT and Tlim at Vmax and
AC. Taken together, results of previous research suggest that other factors must also influence Tlim at Vmax.

Evaluation of equation 3 suggests that AC should be explained by Tlim at Vmax, Vmax, and/or AT. Three investigations evaluated these relationships (Billat et al., 1995; Hill & Rowell, 1996; Renoux, et al., in press). Billat et al. (1995) and Renoux et al. (in press) reported no significant correlation between AC and Tlim at Vmax. Hill and Rowell (1996) reported a significant, positive relationship between AC and Tlim at Vmax. Once again, AC could not be completely explained by these factors alone.

It is not clear exactly which physiological factors contribute to Tlim at Vmax. If the physiological significance of Tlim at Vmax could be determined, it could be used in designing training programs and in deciding training intensities. Furthermore, it would be convenient if only one incremental test and one test at 100% of Vmax could be used to determine AC.

The purpose of this investigation was to determine if Tlim at Vmax was explained by AC, Vmax, AT and/or a combination variable. A second purpose was to determine if AC could be predicted by Tlim at Vmax, Vmax, AT and/or a combination variable.
CHAPTER III

METHODS AND MATERIALS

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

Overview

AT, VO$_2$max, and Vmax were determined in an incremental treadmill test. Vmax was defined as the speed at which VO$_2$max was first elicited in that test. Each participant performed five tests at different percentages of Vmax (100%, 100%, 110%, 105%, and 95%). Tests were separated by at least 24 h and were performed at the same time of day for each participant. All tests were performed in a temperature and humidity controlled laboratory. For all tests, Tlim and accumulated VO$_2$ were calculated. Estimates of O$_2$ deficit, the criterion measure of AC, were determined from the results of the constant velocity tests. The relationships among Tlim at Vmax, O$_2$ deficit, AT, and various forms of these variables were determined.
Participant Characteristics

Participants were 17, male and female volunteers who ran 25 km or more per week. The investigation was approved by the University Institutional Review Board, and all participants provided voluntary written informed consent prior to data collection. Participants' age, height, and weight were recorded before every test.

Data Collection Procedures

Calculation of $\text{VO}_{2\text{max}}, V_{\text{max}}$ and AT

All participants performed an incremental treadmill test in order to directly determine $\text{VO}_{2\text{max}}$. Incremental tests were performed until exhaustion at a 0% slope on a Quinton model 633 treadmill (Seattle, WA). The initial velocity was set at 8 km·h$^{-1}$ for the women and 10 km·h$^{-1}$ for the men. The tests and corresponding data collection started as soon as participants released their grasp on the handrails. Participants received strong verbal encouragement to continue as long as possible. All stages were 1 min in duration, and the velocity was increased by 1 km·h$^{-1}$ at the end of every stage. The test was terminated when participants grasped the handrails. All treadmill velocities were verified by stopwatch recordings of 20 belt revolutions. Heart rates were monitored using a Marquette Max-1® Stress System (Milwaukee, WI, USA) and were recorded from a five-lead EKG during each stage of exercise.

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. $O_2$ and $CO_2$ analyzers
were calibrated according to the manufacturer's instruction using gases of known concentration. $\text{VO}_2$, $\text{VCO}_2$, $V_E$, and RER were calculated 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 for $\text{VO}_2$.

Similarly, the highest 30-s average for $V_E$, $\text{VCO}_2$, and RER were taken as $V_E\text{max}$, $\text{VCO}_2\text{max}$, 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. $V_{\text{max}}$ was determined as the velocity at which $\text{VO}_2\text{max}$ was first reached. If the highest 30-s average for $\text{VO}_2\text{max}$ fell over two velocities, $V_{\text{max}}$ was chosen as the lower of the two velocities.

**Determination of ventilatory anaerobic threshold**

Three different values for the ventilatory anaerobic threshold were determined. They were referred to as AT1, AT2 and AT3. AT1 and AT2 were defined using the method by Skinner and McLellan (1980). AT1 was defined as the treadmill velocity and corresponding $\text{VO}_2$ at which there was a breakaway in $V_E$, an increase in $V_E/\text{VO}_2$, and an initial increase in percent of $O_2$ in the expired air, plotted against time. AT2 was identified by a second breakaway in $V_E$, an increase in $V_E/\text{VCO}_2$, and an initial decrease in $\%\text{CO}_2$ in the expired air, plotted against time. AT3 was defined as the point above which $\text{VCO}_2$ began to increase more rapidly relative to $\text{VO}_2$ (Beaver, Wasserman, & Whipp, 1986).

AT1, AT2, and AT3 were identified separately by two investigators. Differences were then resolved by conference between the two investigators.
Tlim and other responses at Vmax in constant velocity tests

Participants performed constant power tests at 95%, 100%, 100% 105%, and 110% of Vmax, each on a separate day. Participants performed the tests in the order of 100%, 100%, 110%, 105%, and 95% of Vmax. The first test at 100% served as a practice trial. Each test began with a 6-min warm-up at one of two different intensities. For some participants, the first test had a warm-up at a velocity associated with approximately 50% of Vmax from the incremental test, and for others a velocity associated with approximately 60% of Vmax. The reason for using these different intensities was to have different submaximal data for the calculation of the VO2:velocity relationship. This allowed for two warm-ups to be run at 50% of VO2max and two to be run at 60% VO2max. Following the warm-up, participants stood on the treadmill and rested for 5 min. During this rest period, treadmill velocity was set at the appropriate percentage of Vmax. The test and corresponding data collection began as soon as participants stepped onto the treadmill and released their grasp on the handrails. Strong verbal encouragement was given to participants throughout the test. Participants were informed of time passed every minute. The treadmill velocity was verified during the test by counting 20 treadmill belt revolutions. The test ended when participants grasped the handrails for support. As in 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. For each test, VO2max, VE max, VCO2max, and maximal RER were recorded as the highest 30-s rolling average.
Determination of oxygen deficit (Medbo et al., 1988)

Each individual’s submaximal data from the warm-ups prior to the constant velocity tests were used to determine the slope (ml·kg·min⁻¹ per m·min⁻¹) of the VO₂:velocity relationship using an SPSS (Chicago, IL, USA) regression procedure. The y-intercept was forced to 5 ml·kg⁻¹·min⁻¹ (Medbo, et al., 1988). The O₂ deficit was calculated as the difference between the total O₂ demand and accumulated VO₂ using the following equation:

\[ \text{O}_2 \text{ deficit (ml·kg}^{-1} \text{)} = \text{total O}_2 \text{ demand (ml)} - \text{accumulated VO}_2 \text{ (ml·kg}^{-1} \text{)} \]  
(eq 4).

The total O₂ demand (ml) was calculated as O₂ demand multiplied by Tlim (min) as illustrated in the equation

\[ \text{total O}_2 \text{ demand (ml)} = \text{O}_2 \text{ demand (ml·kg}^{-1} \text{)} \cdot \text{Tlim (min)} \]  
(eq 5).

The O₂ demand (ml·kg⁻¹·min⁻¹) was determined by extrapolation of the VO₂:velocity relationship to the intensity used in the constant velocity test (i.e. 95% Vmax, 100% Vmax, 105% Vmax, and 110% Vmax) and was written as

\[ \text{O}_2 \text{ demand (ml·kg}^{-1} \text{·min}^{-1}) = \]  
\[ (\text{velocity (m·min}^{-1}) \cdot \text{slope (ml·kg}^{-1} \text{·min}^{-1} \text{ per m·min}^{-1}) + 5 \text{ ml·kg}^{-1} \text{·min}^{-1}) \]  
(eq 6).

Steady state VO₂ was the average of the four steady state 15-s values for VO₂ during the warm-up. Steady state VO₂ and calculated treadmill velocities were used in calculation of slope. Accumulated VO₂ was calculated for each constant velocity for each participant. Accumulated VO₂ was calculated using 15-s means and breath-by-breath data. All 15-s values for VO₂ from the beginning to the end of the test were averaged and
multiplied by time. Extra VO₂ values from the beginning and end of the test were obtained from the breath-by-breathe. These values were averaged separately and were each multiplied by the number of extra values divided by 60. The first value calculated from the 15-s averages, and the two values calculated from the breath-by-breath were added together to give accumulated VO₂.

Using these conventional procedures discussed above, each participant was provided one value for O₂ deficit for each of the constant velocity tests. The coefficient of variation was calculated for the four values, and the mean of the three values with the lowest coefficient of variation was determined.

**Determination of oxygen deficit (Hill, 1996)**

Each participant had four sets of values for accumulated VO₂, velocity, and Tlim. These four sets of values were fit to the following regression model:

\[
\text{accumulated VO}_2 = (O_2 \text{ demand (ml·kg}^{-1}\text{·min}^{-1} \text{ per m·min}^{-1}) \cdot \text{velocity (m·min}^{-1}) \cdot \text{Tlim (min)}) - O_2 \text{ deficit (ml·kg}^{-1})
\]  (eq 7).

The nonlinear regression procedure on SPSS was used. Accumulated VO₂ was calculated as explained previously. For each participant, values for the parameters of O₂ deficit and O₂ demand were derived using an iterative least squares procedure on SPSS.

The regression procedure also generated a standard error of estimate (SEE) for each parameter and an R² describing the overall fit of the data to the model. With this method, each participant was provided one value for O₂ deficit based on the results of four maximal tests and also one value for each of four possible combinations of three tests.
The four combinations were derived by obtaining the mean \( O_2 \) deficit value of three of the tests, excluding one of the tests each time. The parameter estimate with the lowest SEE and the model with the highest \( R^2 \) was determined. The corresponding value for \( O_2 \) deficit was selected for each participant.

**Statistical Analysis**

Pearson correlations were calculated in order to determine if Tlim at Vmax was related to AT, AC, Vmax and/or a combination variable \( [O_2 \text{ deficit} \cdot (Vmax - vAT)] \). Several different forms for the combination variables were used -- Vmax and VO\(_2\)\text{max} were used, and vAT was alternately expressed as a velocity, an oxygen uptake, a percentage of Vmax, and a percentage of VO\(_2\)\text{max}, for AT1, AT2, and AT3. This yielded 80 possible combination variables. Patterns were identified to see which variables were involved in combinations with high correlations.

A Pearson correlation was also used in order to determine if \( O_2 \) deficit could be predicted from Tlim at Vmax, Vmax, AT and/or a combination variable \([\text{Tlim} \cdot (Vmax - vAT)]\). There were 20 possible combinations. Again, significant correlations were identified.

All correlations were calculated using a SAS statistical program (Cary, NC). Statistical significance was set at the 0.05 level. Throughout this paper, all results are presented as means \( \pm \) SD.
CHAPTER IV

RESULTS

The purpose of this study was to determine if Tlim at Vmax was influenced by AT, AC, Vmax, and/or a combination variable \[ AC \cdot (Vmax - vAT)^{1}\]. A second purpose was to determine if AC could be estimated or predicted from Tlim at Vmax, Vmax, AT and/or a combination variable \[ Tlim \cdot (Vmax - vAT) \]. The results of this study are presented in this chapter.

Mean Values for Descriptive Variables, Physiological Measures, and Derived Parameters

Mean values for age, height and weight for all participants were 25 ± 6 yr, 173.4 ± 10.16 cm, and 71.6 ± 13.3 kg, respectively. Individual values are presented in Appendix A. Individual values for men and women are also presented in Appendix A. Women were of mean age 23 ± 2 yr, height 165 ± 8 cm, and weight 59.5 ± 3.7 kg. Men were of mean age 27 ± 7 yr, height 180 ± 6 cm, and weight 80.0 ± 10.6 kg. Values for \( V0_{max} \) (ml-min and ml·kg·min), Vmax, Tlim at Vmax, and AC for all participants are also presented in this appendix.

\( V0_{max} \)

For all participants, mean \( V0_{max} \) from the incremental test was 3179 ± 804 ml·min⁻¹ or 44.3 ± 7.6 ml·kg⁻¹·min⁻¹. The mean value for \( V0_{max} \) in female participants was 2428 ± 314 ml·min⁻¹ or 40.7 ± 4.1 ml·kg⁻¹·min⁻¹. The mean value for \( V0_{max} \) in
male participants was $3705 \pm 581 \text{ ml-min}^{-1}$ or $46.9 \pm 8.6 \text{ ml-kg}^{-1}\text{-min}^{-1}$. The criteria for achieving VO_{2max} were met by all participants.

**Vmax**

The mean value for Vmax for all participants was $271 \pm 28 \text{ m-min}^{-1}$ ($4.5 \text{ m-s}^{-1}$, 16.3 km-h^{-1}, 10.1 mile-h^{-1}). Mean values for Vmax in female and male participants were $250 \pm 20 \text{ m-min}^{-1}$ ($4.2 \text{ m-s}^{-1}$, 15 km-h^{-1}, 9.3 mile-h^{-1}) and $285 \pm 23 \text{ m-min}^{-1}$ ($4.8 \text{ m-s}^{-1}$, 17.1 km-h^{-1}, 10.6 mile-h^{-1}), respectively.

**Tlim at Vmax**

Mean Tlim at Vmax was $229 \pm 121 \text{ s}$ for all participants, with values ranging from 96 to 534 s. Mean Tlim was $213 \pm 149 \text{ s}$ for female participants and $240 \pm 105 \text{ s}$ for male participants.


Mean values for O_2 deficit, as determined using the method of Hill (1996), for all participants, were $2961 \pm 1902 \text{ ml}$ and $41 \pm 26 \text{ ml-kg}^{-1}$. Mean values for O_2 deficit using the method defined by Medbo et al. (1988) were $2875 \pm 1330 \text{ ml}$ and $40 \pm 19 \text{ ml-kg}^{-1}$. Mean values for O_2 deficit are presented in Appendix D.

**AT**

The criteria for AT1 could not be met by three participants (one man and two men) because they were missing values for AT1. Therefore, for mean values and correlations involving AT1, the number of participants was 14 rather than 17.

Participants’ vAT1 was $162 \pm 19 \text{ m-min}^{-1}$ ($59 \pm 4\%$ of Vmax) and was associated with a VO_{2} of $1908 \pm 469 \text{ ml-min}^{-1}$ ($63 \pm 8\%$ of VO_{2max}). Participants’ vAT2 was $199 \pm$
28 m·min⁻¹ (74 ± 8% of Vmax) and was associated with a VO₂ of 2576 ± 610 ml·min⁻¹ (82 ± 8% of VO₂max). Their vAT3 was 182 ± 24 m·min⁻¹ (67 ± 6% of Vmax) and was associated with a VO₂ of 2349 ± 679 ml·min⁻¹ (74 ± 11% of VO₂max).

Relationships Among Variables

For analyses involving all participants (N = 17), correlations were significant at the .05 level when r ≥ 0.48. Correlations were significant at the .01 level when r ≥ 0.63. For analyses involving ATI (N = 14), correlations were significant at the .05 level when r ≥ 0.52. Correlations were significant at the .01 level when r ≥ 0.66.

Relationship Between Tlim at Vmax and Individual Variables

Correlations observed between Tlim at Vmax and the individual and combination variables are presented in Table 2. The correlation between Tlim at Vmax and O₂ deficit, calculated using the method of Medbo et al. (1988), was 0.71 for O₂ deficit in ml·kg⁻¹ and 0.69 for O₂ deficit in ml. There was no significant correlation between Tlim at Vmax and O₂ deficit calculated using the Hill (1996) method (r ≤ 0.48).

There was no correlation between Tlim at Vmax and VO₂max (r = 0.05, p = 0.85). There was also no correlation between Tlim at Vmax and Vmax (r = -0.13, p = 0.63).

The highest correlation between Tlim and AT was with AT1 expressed as a percentage of Vmax (r = 0.38), but the correlation was not significant (p = 0.18). In general, correlations between Tlim at Vmax and AT were between 0.11 and 0.38, and none were significant.
TABLE 2. Correlation coefficients between Tlim at Vmax and individual and combination variables

<table>
<thead>
<tr>
<th>Medbo O₂ deficit (ml·kg⁻¹)</th>
<th>Hill O₂ deficit (ml·kg⁻¹)</th>
<th>Vmax (m·min⁻¹)</th>
<th>VO₂max (ml·kg⁻¹·min⁻¹)</th>
<th>AT (%Vmax)</th>
<th>Combination Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tlim at Vmax</td>
<td>0.71</td>
<td>0.28</td>
<td>-0.13</td>
<td>-0.05</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Note: The combination variable was in the form $[O_2 \text{ deficit Medbo et al. (ml) \cdot (Vmax - vAT2)}]$.

**Relationship between Tlim at Vmax and combination variables**

The highest correlation between Tlim and the combination variable from equation 1 was with the variable expressed as $[O_2 \text{ deficit Medbo et al. (1988) (ml) \cdot (Vmax - vAT2)}]$ ($r = 0.87$). Another significant correlation between Tlim and the combination variable from equation 1 was with the variable expressed as $[O_2 \text{ deficit Medbo et al. (1988) (ml·kg}^{-1}) \cdot (Vmax - vAT2)^{+}]$ ($r = 0.85$). In general, most of the significant relationships involved O₂ deficit calculated using the Medbo et al. (1988) method and either AT2 or AT3 expressed in different forms. Other relationships between Tlim at Vmax and the combination variables are presented in Appendix B.

**Relationship between AC and Individual Variables**

Table 3 presents correlations between AC and the individual and combination variables. There was a correlation of 0.71 between O₂ deficit (ml·kg⁻¹) calculated using the method by Medbo et al. (1988) and Tlim at Vmax. O₂ deficit (ml) was also correlated with Tlim at Vmax ($r = 0.69$).

There were no significant correlations between O₂ deficit and Vmax.

Furthermore, there were no significant correlations between O₂ deficit and VO₂max.
The highest correlation between $O_2$ deficit and AT was with $O_2$ deficit (ml) calculated using the Medbo et al. (1988) method and AT1 expressed as a velocity. The correlation was 0.66 ($p = 0.01$).

**TABLE 3. Correlation coefficients between AC and individual and combination variables**

<table>
<thead>
<tr>
<th>Vmax (m·min$^{-1}$)</th>
<th>Tlim at Vmax (s)</th>
<th>VO$_{2\text{max}}$ (ml·kg$^{-1}$·min$^{-1}$)</th>
<th>AT (vel at AT1)</th>
<th>Combination Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>O$_2$ deficit Hill (1996) (ml·kg$^{-1}$)</td>
<td>0.27</td>
<td>0.28</td>
<td>-0.02</td>
<td>0.61</td>
</tr>
<tr>
<td>O$_2$ deficit Medbo et al. (1988) (ml·kg$^{-1}$)</td>
<td>-0.09</td>
<td>0.71</td>
<td>-0.11</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Note: The Hill (1996) $O_2$ deficit was correlated with the combination variable in the form $[T\text{lim} \cdot (\% V\text{max} \text{ at AT1})]$. The Medbo et al. (1988) $O_2$ deficit was correlated with the combination variable in the form $[T\text{lim} \cdot (\% VO_{2\text{max}} \text{ at AT3})]$.

**Relationship between AC and Combination Variables**

The highest correlation between $O_2$ deficit and any form of the combination variable from equation 2 was when the variable was expressed as $[T\text{lim} \cdot (V\text{max} - CV)]$, and $O_2$ deficit (ml·kg$^{-1}$) was calculated using the Medbo et al. (1988) method ($r = 0.78$). Since tests were done at several different intensities in this investigation, CV could be calculated. Furthermore, the combination could be expressed in its “proper” form.

Although this was not a specific purpose of this investigation, this combination variable did result in the highest correlation. Several significant correlations were observed between $O_2$ deficit and combination variables which involved AT2 or AT3.

Relationships between $O_2$ deficit and the combination variables are presented in Appendix C.
CHAPTER V

DISCUSSION

The purpose of this investigation was to evaluate if and how AC, Vmax, AT and/or a combination variable explained inter-individual variability in Tlim at Vmax. The second purpose of this investigation was to determine if AC could be estimated from Tlim at Vmax, Vmax, AT and/or a combination variable. If AC could be estimated from the combination variable, this would mean that only two tests (one incremental treadmill test and one constant velocity test) would be necessary to predict AC. A relationship should exist between Tlim at Vmax and these physiological factors, and AC should also be predicted from these factors. The goal of this investigation was to determine if, in fact, a relationship existed between these variables. O2 deficit was used as the criterion measure of AC.

Participants performed one incremental treadmill test to determine VO2max and Vmax. Participants also performed constant velocity tests at Vmax and three different percentages of Vmax in order to determine their O2 deficit and Tlim at Vmax. Relationships among Tlim at Vmax, AC, AT, Vmax and various combination variables were described using Pearson correlation coefficients.

Comparison of Values with Those in the Literature

Values obtained in this investigation were compared to values from previous research. The mean value for Vmax in this investigation (271 m·min⁻¹) was equal to that
obtained by Hill and Rowell (1996) (271 m·min⁻¹). However, these values were lower than those reported in other studies (Billat, et al., 1994; Billat, et al., 1994a, 1994b; Billat, et al., 1995; Renoux, et al., in press) in which mean values ranged from 350 to 367 m·min⁻¹. The mean value for VO₂max (44 ml·kg⁻¹·min⁻¹) was also much lower in this investigation in comparison to previous studies (Hill & Rowell, 1996; Billat, et al., 1994; Billat, et al., 1994a, 1994b; Billat, et al., 1995; Renoux, et al., in press) in which mean values ranged from 68 to 75 ml·kg⁻¹·min⁻¹. Mean Tlim (229 s) was lower in this investigation when compared to previous studies (Billat, et al., 1994; Billat, et al., 1994a, 1994b; Billat, et al., 1995). Previous studies reported values ranging from 321 s to 404 s. Mean Tlim was similar, however, to values obtained by Hill and Rowell (1996) and Renoux et al (in press) (290 s and 269 s, respectively). The mean values for vAT1 and vAT2 in this investigation were similar to those reported by Hill and Rowell (1996) (162 m·min⁻¹, 198 m·min⁻¹ and 165 m·min⁻¹, 200 m·min⁻¹, respectively). However, these values were lower than those reported from previous research (Billat, et al., 1994; Billat, et al., 1994b; Billat, et al., 1995) in which values ranged from 267 to 283 m·min⁻¹. Finally, mean O₂ deficit values, as calculated using the method by Medbo et al. (1988), were similar in this investigation to values reported by Hill and Rowell (1996) (40 ml·kg⁻¹ and 42 ml·kg⁻¹, respectively). One reason that might have accounted for the attainment of lower values in this investigation was that, unlike this investigation, previous studies used elite or sub-elite participants in their research.
Relationship between Tlim at Vmax and individual variables

The results of this present investigation indicated no relationship between Tlim at Vmax and VO$_2$max (ml·min$^{-1}$ or ml·kg$^{-1}$·min$^{-1}$). These results are consistent with research by Billat et al. (1994) who also found no correlation between Tlim at Vmax and VO$_2$max (ml·kg$^{-1}$·min$^{-1}$). Two studies (Hill & Rowell, 1996; Renoux, et al., in press) reported significant positive relationships between Tlim at Vmax and VO$_2$max.

There was a negative correlation between Tlim at Vmax and Vmax in this investigation. These results were consistent with previous research (Billat, et al., 1994; Billat, et al., 1994a, 1995; Renoux, et al., in press). A negative relationship between Tlim at Vmax and Vmax indicates that as Vmax increases, Tlim at Vmax decreases. Theoretically, it seems that Tlim at Vmax should be the same for all individuals because all individuals should be running at the same relative velocity. However, AC also contributes to Tlim at Vmax at intensities greater than AT. The coefficient of variation in Tlim at Vmax in this investigation was large (53%). This could indicate that Vmax was overestimated for some individuals.

No significant relationships were reported in this investigation between Tlim at Vmax and AT1, AT2 or AT3, when AT was expressed as a VO$_2$, a velocity, a percentage of VO$_2$max or a percentage of Vmax. These findings are consistent with those of Billat et al. (1995). They also reported no significant correlation between Tlim at Vmax and AT, when AT was expressed as a percentage of Vmax or a percentage of VO$_2$max.

Results from this investigation revealed that Tlim at Vmax was related to O$_2$ deficit (ml and ml·kg$^{-1}$), when O$_2$ deficit was defined using a modification of the method.
of Medbo et al. (1988). Renoux et al. (in press) reported a significant correlation between Tlim at Vmax and AC. The criterion measure for AC in their investigation was time to exhaustion at 120% of Vmax. Billat, et al. (1995) reported no significant correlation between Tlim at Vmax and AC when the criterion measure for AC was the y-intercept of the relationship between running distance and Tlim. Hill and Rowell (1996) reported that no more than 26% of the variability in Tlim at Vmax was explained by differences in AC, as reflected by $O_2$ deficit. No significant correlation resulted in this investigation between Tlim at Vmax and $O_2$ deficit, when $O_2$ deficit was described using the method of Hill (1996).

**Relationship between Tlim at Vmax and combination variables**

Several relationships were reported in this investigation between Tlim at Vmax and the combination variables. This suggested that Tlim at Vmax was explained, to some degree, by a combination of AT, AC and Vmax. Several different forms of the variables were used to evaluate these relationships. AC ($O_2$ deficit) was determined using the Hill (1996) method or the Medbo et al. (1988) method. Both methods could be provided in ml or ml·kg$^{-1}$. AT could be AT1, AT2, or AT3 and could be expressed as a velocity, a $VO_2$ (ml·min$^{-1}$), a percentage of $VO_2$max, or a percentage of Vmax. $VO_2$max (ml·kg$^{-1}$·min$^{-1}$) and Vmax (m·min$^{-1}$) were also used in the combination variables. The choice of combination variables affected the results.

Very few significant correlations existed between Tlim at Vmax and the combination variable in any form when $O_2$ deficit was calculated using the Hill (1996) method. There were several significant correlations, however, that resulted between Tlim
at Vmax and various forms of the combination variable when the Medbo et al. (1988) $O_2$ deficit method was used. The majority of these relationships involved either AT2 or AT3 expressed as a percentage of Vmax or VO$_2$max. This is important because runners whose AT2 and AT3 are at higher percentages of VO$_2$max and Vmax should run longer before reaching exhaustion compared to those runners who reach AT2 and AT3 at lower percentages of VO$_2$max and Vmax. Hill and Rowell (1996) reported that 36% of the variability in Tlim at Vmax was explained by the combination variable.

**Relationship between AC and individual variables**

No significant relationships resulted in this investigation between $O_2$ deficit calculated using the Medbo et al. (1988) or the Hill (1996) method and VO$_2$max or Vmax. Relationships did result between the value calculated using the Medbo et al. (1988) and Hill (1996) $O_2$ deficit method and AT1 expressed as a velocity. This suggests that the higher the velocity at AT1, the greater the value for $O_2$ deficit. This is important to coaches, fitness evaluators and athletes because apparently training that results in an increase in vAT1 also will increase AC.

The value calculated using the Medbo et al. (1988) method of $O_2$ deficit was also significantly related to Tlim at Vmax. This suggests that the greater the value for $O_2$ deficit, the longer the Tlim at Vmax. This makes sense, but a longer Tlim at Vmax might also reflect a higher AT relative to Vmax. In order to increase $O_2$ deficit, coaches or fitness evaluators should train athletes well above the AT. Billat, et al. (1995) reported a significant correlation between AC and Tlim at 105% of Vmax but not between AC and Tlim at 100% of Vmax. The criterion measure for AC was the y-intercept of the
relationship between running distance and Tlim. Hill and Rowell (1996) reported a significant correlation between \( O_2 \) deficit and Tlim at \( V_{\text{max}} \), but they said that only 26% of the variability in \( O_2 \) deficit was explained by Tlim at \( V_{\text{max}} \). Renoux et al. (in press) reported a significant correlation between AC and Tlim at 100% of \( V_{\text{max}} \), when the criterion measure was time to exhaustion at 120% of \( V_{\text{max}} \). It is difficult to compare results from this investigation to results from previous studies, because unlike previous research, the criterion measure for AC in this investigation was \( O_2 \) deficit.

Results from this investigation and previous investigations indicate that AC is related to the velocity sustained at AT1 and Tlim at \( V_{\text{max}} \). Neither of these factors alone, however, can completely predict AC.

Relationship between AC and combination variables

Several relationships were reported between values calculated using the Medbo et al. (1988) \( O_2 \) deficit method and the combination variable expressed in different forms. Values calculated using the Medbo et al. (1988) \( O_2 \) deficit method were related to the combination variables that expressed the difference between \( V_{\text{max}} \) and the velocity at AT2 and AT3. Significant correlations were also reported between values calculated using the Medbo et al. (1988) method and AT2 and AT3 expressed as a percentage of \( V_{\text{max}} \) and a percentage of \( V_{\text{O}_2\text{max}} \). In this investigation, a correlation of 0.77 resulted between the value calculated using the Medbo et al. (1988) \( O_2 \) deficit method (ml·kg\(^{-1}\)) and the combination variable in the form \([\text{Tlim} \cdot (\text{AT3}_{\text{VO}_2} \cdot (\text{VO}_2\text{max} \cdot 100))]\). In this combination variable, AT was used in order to test the hypothesis that \( O_2 \) deficit could be estimated based on the results of only two tests. When CV replaced AT in the form \([\text{Tlim} \cdot (\text{CV}_{\text{AT3}} \cdot (\text{VO}_2\text{max} \cdot 100))]\).
A correlation of 0.78 resulted between $O_2$ deficit and the combination variable. The fact that a higher correlation resulted with CV than AT suggests one of two things. First of all, AT may have not been measured very well or it is not appropriate to substitute AT for CV. However, AT2 should be almost equal to CV, and the values were similar in this investigation (198 m·min$^{-1}$ and 224 m·min$^{-1}$, respectively). If AT cannot justifiably replace CV, it makes it impossible to estimate AC from only one incremental test and one constant velocity test. Hill and Rowell (1996) reported that only 45% of the variance in $O_2$ deficit, as described using the Medbo et al. (1988) method, could be explained by the combination variable in the form $[T_{lim} \cdot (100\% - \% V_{O_2,max} \text{ at AT2})]$. The highest correlation they found between $O_2$ deficit and any form of the combination variable was 0.67 ($p < 0.01$). Very few relationships were reported between values calculated using the Hill (1996) method and various forms of the combination variable. One explanation for the lack of significant correlations might be that the Medbo et al. (1988) $O_2$ deficit method estimates $O_2$ demand by extrapolating the linear relationship between exercise intensity and the steady state $O_2$ uptake at submaximal intensities. The Hill (1996) $O_2$ deficit method estimates $O_2$ demand based only on the results of exhaustive supramaximal tests using an iterative least squares regression technique. Both Hill (1996) and Medbo et al. (1988) had similar values for $O_2$ deficit, but they both also had a range of values that were lower and higher than expected. There was no correlation between values obtained using the two methods, and it therefore makes sense that each method provided only some valid results.
In general, correlations reported in this investigation between $O_2$ deficit and various forms of the combination variable were low. AC cannot be completely predicted, therefore, by combinations of these variables. Several reasons could account for the low correlations among the individual and combination variables. First of all, according to Green and Dawson (1933), $O_2$ deficit is not a very reliable measure. Two different methods of $O_2$ deficit were used in this investigation. If one or both of these methods are not reliable, then it is difficult to obtain valid estimates of the factors that determine $T_{lim}$ at $V_{max}$. Furthermore, $AT$ was used in place of critical velocity in this investigation, as suggested by Billat et al. (1995). These two factors are related but are not synonymous (Hill, 1993). Results from this investigation indicated a higher correlation between $O_2$ deficit and a combination involving CV than those combinations which involved AT. This either suggests that AT was not measured very well or that it was not appropriate to substitute AT for CV. AT replaced CV, however, in order to test the hypothesis that $O_2$ deficit could be estimated based on the results of only two tests. Another reason that accounted for the low correlations was that $O_2$ demand was extrapolated from the results of only four 6 min submaximal bouts. Medbo et al. (1988) has recommended 10 to 20 submaximal bouts to estimate $O_2$ demand. Therefore, more submaximal bouts of longer duration may have been more useful in extrapolating $O_2$ demand. In addition, there is difficulty in accurately determining $V_{max}$, and $V_{max}$ may not be a reliable measure (Billat, et al. 1994b). This makes it difficult to obtain valid estimates of AC or factors that determine $T_{lim}$ at $V_{max}$. Furthermore, the attainment of $v_{AT}$ and $V_{max}$ were limited to the increments that were used in the incremental test. A final reason that may
have accounted for the low correlations between $O_2$ deficit and various forms of the combination variable is that the critical power concept may not be "perfect". The critical power concept suggests that a relationship exists between velocity and time and that $T_{lim}$ at $V_{max}$ should be predicted completely by $V_{max}$, $AC$, and/or $AT$. Therefore, it follows that $AC$ should also be predicted by a combination of $T_{lim}$ at $V_{max}$, $V_{max}$, and/or $AT$. Theoretically, this makes sense, but other physiological variables may also help explain $T_{lim}$ at $V_{max}$ and help to predict $AC$.

**Summary**

The purpose of this investigation was to answer four important physiological questions:

1. "Is $T_{lim}$ related to $AC$, $V_{max}$ and/or $AT$?"
2. "Is $T_{lim}$ explained by a combination variable in the form $[AC \cdot (V_{max} - vAT)^{-1}]$?"
3. "Is $AC$ related to $T_{lim}$ at $V_{max}$, $V_{max}$ and/or $AT$?"
4. "Is $AC$ predicted by a combination variable in the form $[T_{lim} \cdot (V_{max} - vAT)]$?"

Several relationships that were expected from this investigation were not observed. Theoretically, $T_{lim}$ at $V_{max}$ should be related to $AC$, $V_{max}$, and/or $AT$. However, results from this investigation demonstrated low correlations or no correlations at all between $T_{lim}$ at $V_{max}$ and $V_{max}$ and/or $AT$. A few significant correlations were reported between $T_{lim}$ at $V_{max}$ and the values obtained using the Medbo et al. (1988) $O_2$
deficit method. Also, the highest correlation between Tlim at Vmax and a single variable
was with O₂ deficit (ml·kg⁻¹), defined using the Medbo et al. (1988) method.

The critical power concept, in its rewritten form, suggests a relationship between
Tlim at Vmax and the combination variable. However, in this investigation, the majority
of significant correlations involved combination variables that used the Medbo et al.
(1988) O₂ deficit method (ml and ml·kg⁻¹). Inter-individual differences in Tlim at Vmax
could not be explained from these variables alone. This either suggests that other
variables other than AC, AT and Vmax influence Tlim at Vmax or that accurate measures
were not obtained of some or all of the variables.

AC should be related to Tlim at Vmax, Vmax, and/or AT. However, few
relationships resulted in this investigation. The highest correlation between O₂ deficit and
a single variable was with Tlim at Vmax. Variance in AC could not be explained by any
of these variables alone.

Finally, according to the critical power concept, AC should be predicted from the
combination variable. AC could not be totally predicted from different combinations of
these variables. Once again, other variables may predict AC or accurate measures may
not have been obtained in this investigation on some or all of the variables. The highest
correlation between AC and any form of the combination variable used the Medbo et al.

Conclusion

Results indicated that either Tlim at Vmax is related to factors other than only
AC, AT, and Vmax or accurate measures of all variables were not obtained. Inter-
individual differences in Tlim at Vmax could not be explained by these factors alone. Furthermore, AC is related to other factors than only Tlim at Vmax, Vmax, and/or AT. As mentioned earlier, accurate measures of all variables may have not been obtained. AC could also not be completely predicted by different combinations of the variables. The critical power concept suggests that these variables alone should be enough to explain inter-individual variability in Tlim at Vmax and to predict AC. However, results from this investigation suggest that other physiological factors are involved. It was concluded, therefore, that results from only two tests would not be sufficient to determine anaerobic capacity. The factors that determine Tlim at Vmax and predict AC must be determined in order to understand the physiological significance of Tlim at Vmax and its role in fitness and in monitoring training programs.

Future Recommendations

Future research would be useful in identifying the physiological significance of Tlim at Vmax. Future research is also needed to determine if the results from one incremental treadmill test and one constant velocity test at Vmax would be enough to get an estimate of AC. It would be interesting to see the results of a study which used the same methods but with elite athletes. Also, it might be helpful to use more than four submaximal bouts to extrapolate O2 demand, and use bouts lasting longer than 6 min. Furthermore, it might be helpful to use smaller increments in the incremental test. It would also be interesting to see results of a study which had the same purpose as this investigation but used field testing. Field testing would be more applicable to athletes. Although Tlim at Vmax is influenced by AT, AC, and/or Vmax to some extent, future
studies are needed to determine the precise relationship. Other factors that influence inter-individual differences in Tlim at Vmax and factors that predict AC need to be identified.
APPENDIX A

MEAN VALUES FOR PARTICIPANT CHARACTERISTICS
TABLE 4. Mean values for all participants (N = 17)

<table>
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<tr>
<th>Variable</th>
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<tbody>
<tr>
<td>Age</td>
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<td>6</td>
</tr>
<tr>
<td>Ht (cm)</td>
<td>173</td>
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</tr>
<tr>
<td>Wt (kg)</td>
<td>71.6</td>
<td>13.3</td>
</tr>
<tr>
<td>$V_O_2^{\text{max}}$ (ml·min$^{-1}$)</td>
<td>3179</td>
<td>804</td>
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<td>$V_O_2^{\text{max}}$ (ml·kg$^{-1}$·min$^{-1}$)</td>
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<td>7.6</td>
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<tr>
<td>$V_{\text{max}}$ (m·min$^{-1}$)</td>
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<tr>
<td>$T_{\text{lim}}$ (s)</td>
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<tr>
<td>$O_2$ def Hill (ml·kg$^{-1}$)</td>
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<td>$O_2$ def Medbo (ml)</td>
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TABLE 5. Mean values for women (N = 7)

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<td>Wt (kg)</td>
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TABLE 6. Mean values for men (N = 10)

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<td>Wt (kg)</td>
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APPENDIX B

CORRELATIONS BETWEEN TLIM AT VMAX

AND COMBINATION VARIABLES
TABLE 7. Correlations between Tlim at Vmax and combination variables (N = 17)

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<tr>
<th>COMB. 1</th>
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<th>COMB. 5</th>
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<td>0.47*</td>
<td>0.57*</td>
<td>0.46*</td>
</tr>
<tr>
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*N = 14
\* \( AT1_{\text{O}_2}\_P = [ AT1_{\text{VO}_2} \cdot (\text{VO}_2\text{max} \cdot 100) ] \)

\* \( AT2_{\text{O}_2}\_P = [ AT2_{\text{VO}_2} \cdot (\text{VO}_2\text{max} \cdot 100) ] \)

\* \( AT3_{\text{O}_2}\_P = [ AT3_{\text{VO}_2} \cdot (\text{VO}_2\text{max} \cdot 100) ] \)

\* \( AT1\_v\_PC = [ vAT1 \cdot (V\text{max} \cdot 100) ] \)

\* \( AT2\_v\_PC = [ vAT2 \cdot (V\text{max} \cdot 100) ] \)

\* \( AT3\_v\_PC = [ vAT3 \cdot (V\text{max} \cdot 100) ] \)

Comb. 1 = [ \( O_2 \) deficit Hill (ml) \cdot (V\text{max} - vAT1)\(^{-1}\) ]

Comb. 2 = [ \( O_2 \) deficit Hill (ml-kg\(^{-1}\)) \cdot (V\text{max} - vAT1)\(^{-1}\) ]

Comb. 3 = [ \( O_2 \) deficit Medbo (ml) \cdot (V\text{max} - vAT1)\(^{-1}\) ]

Comb. 4 = [ \( O_2 \) deficit Medbo (ml-kg\(^{-1}\)) \cdot (V\text{max} - vAT1)\(^{-1}\) ]

Comb. 5 = [ \( O_2 \) deficit Hill (ml) \cdot (V\text{max} - vAT2)\(^{-1}\) ]

Comb. 6 = [ \( O_2 \) deficit Hill (ml-kg\(^{-1}\)) \cdot (V\text{max} - vAT2)\(^{-1}\) ]

Comb. 7 = [ \( O_2 \) deficit Medbo (ml) \cdot (V\text{max} - vAT2)\(^{-1}\) ]

Comb. 8 = [ \( O_2 \) deficit Medbo (ml-kg\(^{-1}\)) \cdot (V\text{max} - vAT2)\(^{-1}\) ]

Comb. 9 = [ \( O_2 \) deficit Hill (ml) \cdot (V\text{max} - vAT3)\(^{-1}\) ]

Comb. 10 = [ \( O_2 \) deficit Hill (ml-kg\(^{-1}\)) \cdot (V\text{max} - vAT3)\(^{-1}\) ]

Comb. 11 = [ \( O_2 \) deficit Medbo (ml) \cdot (V\text{max} - vAT3)\(^{-1}\) ]

Comb. 12 = [ \( O_2 \) deficit Medbo (ml-kg\(^{-1}\)) \cdot (V\text{max} - vAT3)\(^{-1}\) ]

Comb. 13 = [ \( O_2 \) deficit Hill (ml) \cdot (AT1\_v\_PC)\(^{-1}\) ]

Comb. 14 = [ \( O_2 \) deficit Hill (ml-kg\(^{-1}\)) \cdot (AT1\_v\_PC)\(^{-1}\) ]

Comb. 15 = [ \( O_2 \) deficit Medbo (ml) \cdot (AT1\_v\_PC)\(^{-1}\) ]

Comb. 16 = [ \( O_2 \) deficit Medbo (ml-kg\(^{-1}\)) \cdot (AT1\_v\_PC)\(^{-1}\) ]
Comb. 17 = \[ O_2 \text{ deficit Hill (ml) \cdot (AT2}_v\text{PC})^i \]
Comb. 18 = \[ O_2 \text{ deficit Hill (ml\cdot kg}^{-1}) \cdot (AT2}_v\text{PC})^i \]
Comb. 19 = \[ O_2 \text{ deficit Medbo (ml) \cdot (AT2}_v\text{PC})^i \]
Comb. 20 = \[ O_2 \text{ deficit Medbo (ml\cdot kg}^{-1}) \cdot (AT2}_v\text{PC})^i \]
Comb. 21 = \[ O_2 \text{ deficit Hill (ml) \cdot (AT3}_v\text{PC})^i \]
Comb. 22 = \[ O_2 \text{ deficit Hill (ml\cdot kg}^{-1}) \cdot (AT3}_v\text{PC})^i \]
Comb. 23 = \[ O_2 \text{ deficit Medbo (ml) \cdot (AT3}_v\text{PC})^i \]
Comb. 24 = \[ O_2 \text{ deficit Medbo (ml\cdot kg}^{-1}) \cdot (AT3}_v\text{PC})^i \]
Comb. 25 = \[ O_2 \text{ deficit Hill (ml) \cdot (VO_2}^{\text{max} - AT1}_V\text{VO}_2)^i \]
Comb. 26 = \[ O_2 \text{ deficit Hill (ml\cdot kg}^{-1}) \cdot (VO_2}^{\text{max} - AT1}_V\text{VO}_2)^i \]
Comb. 27 = \[ O_2 \text{ deficit Medbo (ml) \cdot (VO_2}^{\text{max} - AT1}_V\text{VO}_2)^i \]
Comb. 28 = \[ O_2 \text{ deficit Medbo (ml\cdot kg}^{-1}) \cdot (VO_2}^{\text{max} - AT1}_V\text{VO}_2)^i \]
Comb. 29 = \[ O_2 \text{ deficit Hill (ml) \cdot (VO_2}^{\text{max} - AT2}_V\text{VO}_2)^i \]
Comb. 30 = \[ O_2 \text{ deficit Hill (ml\cdot kg}^{-1}) \cdot (VO_2}^{\text{max} - AT2}_V\text{VO}_2)^i \]
Comb. 31 = \[ O_2 \text{ deficit Medbo (ml) \cdot (VO_2}^{\text{max} - AT2}_V\text{VO}_2)^i \]
Comb. 32 = \[ O_2 \text{ deficit Medbo (ml\cdot kg}^{-1}) \cdot (VO_2}^{\text{max} - AT2}_V\text{VO}_2)^i \]
Comb. 33 = \[ O_2 \text{ deficit Hill (ml) \cdot (VO_2}^{\text{max} - AT3}_V\text{VO}_2)^i \]
Comb. 34 = \[ O_2 \text{ deficit Hill (ml\cdot kg}^{-1}) \cdot (VO_2}^{\text{max} - AT3}_V\text{VO}_2)^i \]
Comb. 35 = \[ O_2 \text{ deficit Medbo (ml) \cdot (VO_2}^{\text{max} - AT3}_V\text{VO}_2)^i \]
Comb. 36 = \[ O_2 \text{ deficit Medbo (ml\cdot kg}^{-1}) \cdot (VO_2}^{\text{max} - AT3}_V\text{VO}_2)^i \]
Comb. 37 = \[ O_2 \text{ deficit Hill (ml) \cdot (AT1}_O\text{2}_P)^i \]
Comb. 38 = \[ O_2 \text{ deficit Hill (ml\cdot kg}^{-1}) \cdot (AT1}_O\text{2}_P)^i \]
Comb. 39 = [ O_2 deficit Medbo (ml) \cdot (AT1_O_2>P)^i ]

Comb. 40 = [ O_2 deficit Medbo (ml\cdot kg^{-1}) \cdot (AT1_O_2>P)^i ]

Comb. 41 = [ O_2 deficit Hill (ml) \cdot (AT2_O_2>P)^i ]

Comb. 42 = [ O_2 deficit Hill (ml\cdot kg^{-1}) \cdot (AT2_O_2>P)^i ]

Comb. 43 = [ O_2 deficit Medbo (ml) \cdot (AT2_O_2>P)^i ]

Comb. 44 = [ O_2 deficit Medbo (ml\cdot kg^{-1}) \cdot (AT2_O_2>P)^i ]

Comb. 45 = [ O_2 deficit Hill (ml) \cdot (AT3_O_2>P)^i ]

Comb. 46 = [ O_2 deficit Hill (ml\cdot kg^{-1}) \cdot (AT3_O_2>P)^i ]

Comb. 47 = [ O_2 deficit Medbo (ml) \cdot (AT3_O_2>P)^i ]

Comb. 48 = [ O_2 deficit Medbo (ml\cdot kg^{-1}) \cdot (AT3_O_2>P)^i ]

Comb. 49 = [ O_2 deficit Hill (ml) \cdot (VO_2\text{max} (ml\cdot kg^{-1}\cdot min^{-1}) - (AT1_VO_2 \cdot WT)^{-1})^{-1} ]

Comb. 50 = [ O_2 deficit Hill (ml\cdot kg^{-1}) \cdot (VO_2\text{max} (ml\cdot kg^{-1}\cdot min^{-1}) - (AT1_VO_2 \cdot WT)^{-1})^{-1} ]

Comb. 51 = [ O_2 deficit Medbo (ml) \cdot (VO_2\text{max} (ml\cdot kg^{-1}\cdot min^{-1}) - (AT1_VO_2 \cdot WT)^{-1})^{-1} ]

Comb. 52 = [ O_2 deficit Medbo (ml\cdot kg^{-1}) \cdot (VO_2\text{max} (ml\cdot kg^{-1}\cdot min^{-1}) - (AT1_VO_2 \cdot WT)^{-1})^{-1} ]

Comb. 53 = [ O_2 deficit Hill (ml) \cdot (VO_2\text{max} (ml\cdot kg^{-1}\cdot min^{-1}) - (AT2_VO_2 \cdot WT)^{-1})^{-1} ]

Comb. 54 = [ O_2 deficit Hill (ml\cdot kg^{-1}) \cdot (VO_2\text{max} (ml\cdot kg^{-1}\cdot min^{-1}) - (AT2_VO_2 \cdot WT)^{-1})^{-1} ]

Comb. 55 = [ O_2 deficit Medbo (ml) \cdot (VO_2\text{max} (ml\cdot kg^{-1}\cdot min^{-1}) - (AT2_VO_2 \cdot WT)^{-1})^{-1} ]

Comb. 56 = [ O_2 deficit Medbo (ml\cdot kg^{-1}) \cdot (VO_2\text{max} (ml\cdot kg^{-1}\cdot min^{-1}) - (AT2_VO_2 \cdot WT)^{-1})^{-1} ]

Comb. 57 = [ O_2 deficit Hill (ml) \cdot (VO_2\text{max} (ml\cdot kg^{-1}\cdot min^{-1}) - (AT3_VO_2 \cdot WT)^{-1})^{-1} ]

Comb. 58 = [ O_2 deficit Medbo (ml) \cdot (VO_2\text{max} (ml\cdot kg^{-1}\cdot min^{-1}) - (AT3_VO_2 \cdot WT)^{-1})^{-1} ]

Comb. 59 = [ O_2 deficit Medbo (ml\cdot kg^{-1}) \cdot (VO_2\text{max} (ml\cdot kg^{-1}\cdot min^{-1}) - (AT3_VO_2 \cdot WT)^{-1})^{-1} ]

Comb. 60 = [ O_2 deficit Medbo (ml\cdot kg^{-1}) \cdot (VO_2\text{max} (ml\cdot kg^{-1}\cdot min^{-1}) - (AT3_VO_2 \cdot WT)^{-1})^{-1} ]
Comb. 61 = [O₂ deficit Hill (ml) • (Vmax - (vAT1 • WT)⁻¹)⁻¹]
Comb. 62 = [O₂ deficit Hill (ml·kg⁻¹) • (Vmax - (vAT1 • WT)⁻¹)⁻¹]
Comb. 63 = [O₂ deficit Medbo (ml) • (Vmax - (vAT1 • WT)⁻¹)⁻¹]
Comb. 64 = [O₂ deficit Medbo (ml·kg⁻¹) • (Vmax - (vAT1 • WT)⁻¹)⁻¹]
Comb. 65 = [O₂ deficit Hill (ml) • (Vmax - (vAT2 • WT)⁻¹)⁻¹]
Comb. 66 = [O₂ deficit Hill (ml·kg⁻¹) • (Vmax - (vAT2 • WT)⁻¹)⁻¹]
Comb. 67 = [O₂ deficit Medbo (ml) • (Vmax - (vAT2 • WT)⁻¹)⁻¹]
Comb. 68 = [O₂ deficit Medbo (ml·kg⁻¹) • (Vmax - (vAT2 • WT)⁻¹)⁻¹]
Comb. 69 = [O₂ deficit Hill (ml) • (Vmax - (vAT3 • WT)⁻¹)⁻¹]
Comb. 70 = [O₂ deficit Hill (ml·kg⁻¹) • (Vmax - (vAT3 • WT)⁻¹)⁻¹]
Comb. 71 = [O₂ deficit Medbo (ml) • (Vmax - (vAT3 • WT)⁻¹)⁻¹]
Comb. 72 = [O₂ deficit Medbo (ml·kg⁻¹) • (Vmax - (vAT3 • WT)⁻¹)⁻¹]
Comb. 73 = [O₂ deficit Hill (ml) • (Vmax - CV)⁻¹]
Comb. 74 = [O₂ deficit Hill (ml·kg⁻¹) • (Vmax - CV)⁻¹]
Comb. 75 = [O₂ deficit Medbo (ml) • (Vmax - CV)⁻¹]
Comb. 76 = [O₂ deficit Medbo (ml·kg⁻¹) • (Vmax - CV)⁻¹]
Comb. 77 = [O₂ deficit Hill (ml) • (100 - PC_CV)⁻¹]
Comb. 78 = [O₂ deficit Hill (ml·kg⁻¹) • (100 - PC_CV)⁻¹]
Comb. 79 = [O₂ deficit Medbo (ml) • (100 - PC_CV)⁻¹]
Comb. 80 = [O₂ deficit Medbo (ml·kg⁻¹) • (100 - PC_CV)⁻¹]
APPENDIX C

CORRELATIONS BETWEEN AC AND COMBINATION VARIABLES
TABLE 8. Correlations between AC and combination variables (N = 17)

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<td>0.42</td>
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<td>(ml·kg⁻¹)</td>
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<td>O₂ DEF HILL</td>
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*N = 14*
* AT1_O2_P = AT1_VO2 \cdot (\text{VO}_2\text{max} \cdot 100)

* AT2_O2_P = AT2_VO2 \cdot (\text{VO}_2\text{max} \cdot 100)

* AT3_O2_P = AT3_VO2 \cdot (\text{VO}_2\text{max} \cdot 100)

* AT1_v_PC = vAT1 \cdot (\text{Vmax} \cdot 100)

* AT2_v_PC = vAT2 \cdot (\text{Vmax} \cdot 100)

* AT3_v_PC = vAT3 \cdot (\text{Vmax} \cdot 100)

* PC-CV = CV \cdot (\text{Vmax} \cdot 100)

Comb. 1 = Tlim \cdot (\text{Vmax} - vAT1)

Comb. 2 = Tlim \cdot (\text{Vmax} - vAT2)

Comb. 3 = Tlim \cdot (\text{Vmax} - vAT3)

Comb. 4 = Tlim \cdot AT1_v_PC

Comb. 5 = Tlim \cdot AT2_v_PC

Comb. 6 = Tlim \cdot AT3_v_PC

Comb. 7 = Tlim \cdot (\text{Vmax} - AT1_VO2)

Comb. 8 = Tlim \cdot (\text{Vmax} - AT2_VO2)

Comb. 9 = Tlim \cdot (\text{VO}_2\text{max} - AT3_VO2)

Comb. 10 = Tlim \cdot AT1_O2_P

Comb. 11 = Tlim \cdot AT2_O2_P

Comb. 12 = Tlim \cdot AT3_O2_P

Comb. 13 = Tlim \cdot (\text{VO}_2\text{max} \cdot \text{ml-kg}^{-1} \cdot \text{min}^{-1}) \cdot (AT1_VO2 \cdot \text{WT})^\dagger

Comb. 14 = Tlim \cdot (\text{VO}_2\text{max} \cdot \text{ml-kg}^{-1} \cdot \text{min}^{-1}) \cdot (AT2_VO2 \cdot \text{WT})^\dagger

Comb. 15 = Tlim \cdot (\text{VO}_2\text{max} \cdot \text{ml-kg}^{-1} \cdot \text{min}^{-1}) \cdot (AT3_VO2 \cdot \text{WT})^\dagger
Comb. 16 = $T_{lim} \cdot (V_{max} - (v_{AT1} \cdot W_T)^{1})$

Comb. 17 = $T_{lim} \cdot (V_{max} - (v_{AT2} \cdot W_T)^{1})$

Comb. 18 = $T_{lim} \cdot (V_{max} - (v_{AT3} \cdot W_T)^{1})$

Comb. 19 = $T_{lim} \cdot (PC_{CV})$

Comb. 20 = $T_{lim} \cdot (V_{max} - CV)$
APPENDIX D

VALUES FOR O₂ DEFICIT
<table>
<thead>
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<th>Subject</th>
<th>Mean $O_2$ Def Hill</th>
<th>SE</th>
<th>Test not used</th>
<th>Mean $O_2$ Def Med</th>
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REFERENCES


Renoux, J., Billat, V., Pinoteau, J., Petit, B., & Koralsztein, J. (in press). Time to exhaustion at 100% and 120% of maximal aerobic speed are inversely correlated with VO$_2$max. European Journal of Applied Physiology.

