A SINGLE TEST FOR THE DETERMINATION OF THE VELOCITY: TIME-TO-
EXHAUSTION RELATIONSHIP

by

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Abstract

Purpose: To determine if a single test is accurate in determining the parameters of the velocity: time-to-fatigue relationship, i.e., critical velocity (CV) and a finite distance that can be covered above CV (D`). **Methods:** Ten healthy subjects completed an incremental test to volitional exhaustion followed by four constant-velocity runs on a treadmill for the determination of CV and D`, as well as an all-out 3-minute test on a track for the determination of end-test velocity (EV) and the distance above end-test velocity (DEV). Eight of the eleven subjects completed a second 3-minute test and one run each at (+) and (-) 95% confidence interval velocities of CV determined from the 1/time model. **Results:** The group mean 1/time model CV (12.8 ± 2.5 km·h^{-1}) was significantly greater than the velocity-time model CV (12.3 ± 2.4 km·h^{-1}; $P < 0.05$), while the velocity-time model W` ($285 \pm 106$ m) was greater than the 1/time model W` (220 ± 112 m; $P < 0.05$). EV (13.0 ± 2.7 km·h^{-1}) and DEV (151 ± 45 m) were not significantly different than the 1/time model CV and W`, respectively. EV was greater than the velocity-time model CV ($P < 0.05$), while the DEV was significantly less than the velocity-time model W` ($P = 0.002$). No difference was found for group mean EV or DEV between the two 3-minute tests ($P > 0.05$), which demonstrated a reliability coefficient of 0.85 for EV and 0.32 for DEV. For the CV (-) 95% run, all subjects reached a steady-state in $\dot{V}O_2$, and completed 900 s of exercise. However, for the CV (+) 95% run, $\dot{V}O_2$ never reached a steady-state, but increased until termination of exercise at 643 ± 213 s with a $\dot{V}O_{2peak}$ close to but significantly lower than $\dot{V}O_{2max}$ ($P < 0.05$). **Conclusion:** CV can be accurately determined using a single 3-minute test, while W` is underestimated with this protocol.

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Chapter 1 - Introduction

A.V. Hill in 1925 originally introduced the notion that an inverse relationship exists between power output and the time that a given power output can be sustained (time-to-exhaustion) (18, 19). This relationship was later examined in isolated muscle groups where the authors observed a power output that could be maintained "for a very long time without fatigue" (termed critical power; CP) as well as a finite amount of work that could be performed above CP (later termed W`) (42). Since being measured in isolated muscles, the power: time-to-exhaustion relationship has been observed in cycling (2, 17, 23, 25, 39-41, 45, 47, 48, 50, 53), swimming (60), rowing (21), knee extension exercise (35, 56), and running (7, 28, 52).

The power: time-to-exhaustion relationship is well defined with a two-parameter hyperbolic function as both a linear and non-linear model. In the non-linear model (power-time), CP is defined as the power asymptote and W` is the curvature constant:

$t = W` / (P - CP)$ **(Equation 1)**

while the linear (1/time) model defines CP as the y-intercept and W` as the slope:

$P = (W`/ t) + CP$ **(Equation 2)**

where *P* represents power output, and *t* represents time-to-exhaustion (61). CP is associated with the muscle's aerobic capacity and is altered with hypoxia (43), hyperoxia (56), endurance training (17, 30, 48), is correlated with indices of aerobic performance (16, 37, 43), and is unaffected by creatine supplementation (39) or glycogen depletion (40).   W` is determined, in part, by intramuscular energy stores of phosphate, glycogen, and oxygen (39, 40, 42) as well as by accumulation of fatigue-inducing metabolites (12, 35). This parameter is altered with creatine supplementation (39), glycogen depletion (40), high intensity exercise training (29), and prior severe exercise (11, 12, 57), while it is unaffected by decreased inspired oxygen availability (43) and endurance training (17, 30, 48), supporting the conclusion that it is predominantly "anaerobic" in nature. Together CP and W` define the power: time-to-exhaustion relationship and theoretically determine the highest sustainable exercise intensity, and demarcate the heavy-severe exercise intensity domain boundary. Above CP, continuous alterations in phosphocreatine [PCr], hydrogen ion [H^+], and inorganic phosphate [Pi] occur, while oxygen uptake ($\dot{V}O_2$) continually rises towards $\dot{V}O_{2max}$. Below CP a general steady-state is achieved

(35, 47). As a result, any exercise above CP will lead to exhaustion or a reduction in power to an intensity $\leq$ CP once W` has been utilized, according to the two-parameter hyperbolic model.

Traditionally the determination of CP required a subject to visit the laboratory on multiple occasions with adequate recovery time between sessions (typically 24 hours). In this protocol $\dot{V}O_{2peak}$ is determined from an initial max test, which is then used to determine the intensities of the constant-load tests. Each subject then completes multiple constant-load tests (typically 3-5) until exhaustion at peri-maximal power outputs. This protocol is time consuming and troublesome for certain study designs (20). For example, intervention studies where the subject's CP is measured before and after an intervening factor requires a minimum of nine testing sessions per subject (2, 17, 23, 29, 38-41, 48). The time consuming nature of this protocol limits the ability to test the effect of a variety of interventions on the power: time-to-exhaustion relationship.

Recently, Vanhatalo et al. (55) developed a single 3-minute all-out cycle ergometer test designed to utilize W`, so that the end-exercise power output would correspond to CP. The author's defined end-test power as the average power output over the final 30 seconds of the 3-minute test, and the work performed above end-test power as the area under the power curve above end-test power. Comparisons between end-test power and CP, as well as work above end-test power and W` revealed no significant differences. These results demonstrate that the 3-minute cycling test can be used to determine both parameters of the power: time-to-exhaustion relationship.

A similar paradigm to that of cycling has been developed for running (the velocity: time-to-exhaustion relationship) where velocity and distance replace power and work, respectively (22, 28). The two-parameter hyperbolic function with equations 1 and 2 can be adapted to running yielding a non-linear model (velocity-time):

$t = D` / (V - CV)$ **(Equation 3)**

and linear model (1/time):

$V = (D`/t) + CV$ **(Equation 4)**

where *V* represents velocity, *t* represents time-to-exhaustion, CV represents critical velocity, and D` represents a finite distance that can be covered above CV. As with CP and W` the determination of the velocity: time-to-fatigue parameters currently requires multiple visits from each subject to the laboratory to complete several constant-velocity runs to exhaustion on a

treadmill. Thus, determining CV poses the same difficulties as does the traditional determination of CP. The difficulties in determining CV could also be one reason why it is not widely used in the athletic arena. A more applicable test may resolve these issues as has done for the determination of CP.

Therefore, the purpose of the present study was to determine if a single all-out running test could be used to accurately determine CV and D`. Specifically we tested the hypotheses that for a single 3-minute all-out running test: (1) the end-test velocity (EV) over the final 30 seconds would not differ significantly from CV determined with the traditional protocol; and (2) the distance above end-test velocity (DEV) would not differ significantly from D` determined with the traditional protocol.

Chapter 2 - Literature Review

Theory of the Power: Time-to-Exhaustion Relationship

   A.V. Hill first described a hyperbolic appearance between power output and the time-to-exhaustion at that power output in the early 1900s (18, 19). The relationship witnessed by A.V. Hill was later quantified and measured in isolated muscle groups during static and dynamic contractions by Monod and Scherrer (42). This landmark study was the first to quantify the relationship witnessed 40 years earlier and to reinforce the existence of a hyperbolic relationship between the power requirement and the time-to-exhaustion. In this study, the authors were able to define two parameters determining muscle performance. One parameter which they termed critical power was defined as a power output that could be maintained for long periods of time without fatigue. The second parameter, W_{lim} (now referred to as W`), was defined as a finite amount of work that can be performed above critical power. In this study it was suggested that critical power represented a "fatigueless" power output that could be maintained indefinitely, while duration was limited above critical power. Moritani (43) expanded this idea to whole body exercise by demonstrating the power: time-to-exhaustion relationship holds true for cycling, in which exercise performance is defined by critical power and W`. After the characterization of the power: time-to-exhaustion relationship for cycling, other modes of exercise were inventively studied with running (28), swimming (60), rowing (21), and knee extension exercise (35, 58) all demonstrating a hyperbolic relationship between their respective units (velocity or power) and the time-to-exhaustion.

   Stemming from the asymptotic nature of these relationships as well as the suggestion of Monod & Scherrer (42), critical power theoretically is a power output that can be maintained indefinitely. However, research has demonstrated that time-to-exhaustion while exercising at critical power is limited within a range of 20 – 60 minutes (3, 6, 25, 27, 32), speculatively due to substrate depletion, thermoregulation, and electrolyte imbalance (47). Nevertheless, the importance of these parameters is demonstrated by their defining of the body's physiological responses to exercise. Critical power demarcates the boundary between the heavy and severe domains of exercise (47), in which exercise above critical power is limited by the magnitude of W`. For this reason the power: time-to-exhaustion relationship is important within the research setting as well as the athletic arena.

Determining the Power: Time-to-Exhaustion Relationship

The power: time-to-exhaustion relationship is simple to determine in that physiological parameters are defined using a cycle ergometer and a stop watch. Typical determination of the power: time-to-exhaustion relationship requires several constant power tests with the subject cycling until exhaustion each time. A minimum of two of these tests may be used in conjunction with the linear 1/time model, however it is generally recommended that four to five tests are used to decrease the chance of error within the modeling (20). These constant power tests are designed to induce exhaustion between 2 – 15 minutes, with at least one test closer to two minutes and one closer to fifteen (47). During these tests the power requirement is fixed and the time-to-exhaustion is recorded from the initiation of the test until the subject can no longer maintain the power output. The data from the rides are then fit with 1/time and power-time equations to determine critical power and W`.

Recently, Vanhatalo et al. (55) demonstrated that critical power and W` can be determined using a 3-minute all-out test on a cycle ergometer. After the initial ramp protocol for the determination of peak oxygen uptake ($\dot{V}O_{2peak}$), a single ride on the ergometer replaces the constant power rides. Using a cycle ergometer in linear mode (where power is dependent upon pedal rate) the work rate is set to achieve 50% Δ (halfway between gas exchange threshold and $\dot{V}O_{2peak}$) at the subject's preferred pedal cadence, and the subject maintains the fastest cadence possible throughout the 3 minutes. Therefore, as high pedal rates are initially achieved the power output is also high (above critical power) and W` is utilized. As W` is completely utilized energy can no longer be provided by these stores, and critical power becomes the highest power output that can subsequently be maintained. In this study the average power output over the final 30 seconds (287 W) was equivalent to critical power (287 W) and the work completed above this power output (15.0 kJ) was equivalent to W` (16.0 kJ; Figure 2 in (55)). With this protocol the parameters of the power: time-to-exhaustion relationship can be determined with two tests (ramp test and 3-minute test) instead of the four to five more conventionally used tests.

Modeling the Power: Time-to-Exhaustion Relationship

Several mathematical models have been utilized to describe the data acquired from the constant power rides in order to define the parameters of the power: time-to-exhaustion

relationship. These mathematical models include a two-parameter hyperbolic model with a linear (61) and non-linear function (42), a three-parameter hyperbolic function (44), and an exponential model (24). The most abundantly used model in the literature is the two-parameter hyperbolic function. This can be expressed as a non-linear power-time function:

$$t = W' / (P - CP) \qquad \textbf{(Equation 5)}$$

where t is time-to-exhaustion, W' is the finite work capacity, P is power, and CP is critical power. In this model the power asymptote represents critical power while the curvature constant represents W'. This function can be also linearized into the 1/time function:

$$P = (W'/t) + CP \qquad \textbf{(Equation 6)}$$

where W' is now represented by the slope of the line and critical power as the y-intercept.

Although the power-time and 1/time models both are derived from the two-parameter hyperbolic model, differences between the parameter estimates have been reported in the literature (7, 16, 26). These differences occur despite both models being fit to the same data. One reason for the discrepancy is thought to lie in incorrectly assigning the independent and dependent variables within the 1/time model (16). In this model, power is assigned as the dependent variable and 1/time as the independent variable; thus the least squares analysis adjusts the error in power during linear regression. However, for the constant power tests power is held constant and the error lies within the measurement of time. In the power-time model, power is correctly assigned as the independent variable and time as the dependent, so that the least squares analysis correctly accounts for the error in time. It has also been demonstrated that when the correlation coefficient is above 0.94, switching the variables for the 1/time model has no significant difference in the parameter outcomes (48).

Mechanisms Determining the Power: Time-to-Exhaustion Relationship

In 1988 Poole et al. (47) studied the physiological responses to exercise spanning critical power. In this study the authors used five constant power rides to determine critical power and W' with the power-time (Equation 1) and 1/time (Equation 2) models. In addition, the subjects performed two additional exercise tests, cycling at critical power and 5% above critical power. While cycling at critical power, blood lactate concentration, bicarbonate concentration, and $\dot{V}O_2$ achieved steady-state values after their initial deviation from resting values, and all of the

subjects completed the allotted 24 minutes. However, cycling at 5% above critical power yielded substantially different results with blood lactate concentration, bicarbonate concentration, and $\dot{V}O_2$ continually changing throughout the test and exhaustion ensuing at 17.7 minutes on average. The concentration of blood lactate at the end of this test was twofold higher than that of the ride at critical power and the peak $\dot{V}O_2$ achieved was not different from the $\dot{V}O_{2peak}$ determined from the ramp test.

The use of ^{31}P-MRS technology has allowed researchers to non-invasively examine the physiological changes that take place within the muscle during exercise. Jones et al. (35) used this technique to examine the muscle's metabolic response during knee extension exercise ~10% above and below critical power. Consistent with previous work, all subjects in this experiment were able to maintain the exercise for the allotted 20 minutes while exercising below critical power, with all of the subjects exhausting prior to the 20 minutes (mean 14.7 ± 7.1 minutes) above critical power. Importantly, the ^{31}P-MRS technique allowed the researchers to measure intramuscular metabolites such as inorganic phosphate (Pi), creatine phosphate (PCr), and pH before, during, and after exercise. With exercise below critical power, Pi rose to a steady-state level after one minute with no further increase for the rest of the 20 minutes. Initially PCr fell at the onset of exercise, to stabilize at 75% of the baseline value within approximately three minutes with no further change for the duration of the test. Intramuscular pH fell at the beginning, but recovered during the exercise with no difference between the final pH and the beginning pH. At just 10% above critical power the intramuscular responses were significantly different. Pi achieved a maximal concentration after three minutes, with the end concentration significantly higher than that seen for the below critical power exercise. PCr never stabilized during the test with a continued fall until exhaustion ensued reaching 26% of baseline values and muscle pH fell precipitously to an average of 6.9 compared to 7.1 below critical power.

The results from these two studies demonstrate that critical power represents the boundary between the heavy and severe intensity domains of exercise. This boundary presents the highest intensity in which steady-state levels can be achieved and exercise can be maintained. Above this threshold $\dot{V}O_2$ will continually increase until the attainment of $\dot{V}O_{2max}$ after which exhaustion will soon follow. In addition, PCr and pH will fall while Pi accumulates until exhaustion ensues. Vanhatalo et al. (56) demonstrated that Pi, PCr, and pH achieve similar

concentrations when exhaustion occurs over a range of work rates, pointing to the accumulation of fatigue inducing metabolites as determining the magnitude of W`.

Creatine monohydrate supplementation has been shown to increase intramuscular PCr stores and enhance high-intensity exercise, allowing Miura et al. (39) to use this intervention to examine the physiological basis of W`. The power: time-to-exhaustion relationship was characterized in each subject before and after supplementation with either 20g of creatine monohydrate or placebo for five days. Critical power was found to be unaltered following creatine supplementation (214 W vs. 207 W) while W` was significantly increased (10.9 kJ vs. 13.7 kJ). In another study by Smith et al. (53) similar results were found with creatine supplementation as W` was increased and critical power was unaffected.

In further examining the physiological basis of the power: time-to-exhaustion relationship, Miura et al. (40) used glycogen depletion to manipulate intramuscular glycogen stores. Glycogen depletion was achieved by cycling for 75 minutes at 60% $\dot{V}O_{2max}$ followed by ~eight one minute bouts of cycling at 115% $\dot{V}O_{2max}$ the night prior to the constant power rides. No significant difference was found between critical power for the two glycogen states (197 W vs. 190 W), but W` was significantly lower following glycogen depletion (12.83 kJ vs. 10.33 kJ).

These studies suggest that W` is determined in part by anaerobic energy stores within the muscle. Above critical power, energy stores within the muscle must be utilized to provide the necessary energy for the power output. Therefore, increasing intramuscular PCr concentration allows for more energy to be utilized from these stores and thus a larger amount of work can be performed prior to exhaustion. Decreasing glycogen stores has the opposite effect, as less energy is available for use and W` is lowered.

Altering the inspired oxygen content provides a way for researchers to examine how oxygen availability affects the two parameters of the power: time-to-exhaustion relationship. Originally, Moritani (43) found that critical power decreased in the presence of a lower oxygen concentration while leaving W` unaltered. Recently, Vanhatalo et al. (56) found that critical power increased (16.1 W vs. 18.0 W) and W` decreased (1.92 kJ vs. 1.48 kJ) during hyperoxia for knee extension exercise. In this study PCr and pH values at fatigue under normoxic and hyperoxic conditions were not significantly different.

Several key findings emerged from these two studies. First, hypoxia only has a deleterious effect on critical power, while hyperoxia has a beneficial effect on critical power and a deleterious effect on W`. These two studies together demonstrate the aerobic nature of critical power as this parameter is sensitive to the inspired oxygen. The finding that PCr and pH achieved the same levels at exhaustion under both conditions supports the notion that W` represents a critical level for these metabolites, and that fatigue occurs with the attainment of these levels.

Accumulating levels of hydrogen ions have been demonstrated to induce fatigue within the muscle (13). To study the effects of acidosis on critical power and W`, scientists have attempted to alter pH within the muscle using sodium bicarbonate ($NaHCO_3$). It was hypothesized that ingestion of $NaHCO_3$ would allow for more work to be completed during the 3-minute all-out test due to an increase in W`. Following ingestion of 0.3 g·kg^{-1} $NaHCO_3$ critical power and W` were both unaffected.

The finding that both parameters of the power: time-to-exhaustion relationship were unaltered by $NaHCO_3$ ingestion suggests pH does not play a major role in determining either parameter. This finding suggests the factors inducing fatigue as W` is utilized might be PCr and/or Pi, as Pi has been shown to induce fatigue within the muscle by competitively inhibiting calcium at its binding site on troponin (1, 13). However, it was noted by the authors that the decrease in pH could have been isolated to the blood and might not have made it into the muscle as it this was not directly assessed. If no alkalosis occurred within the muscle this could explain why no alterations in critical power and W` occurred (58). Therefore hydrogen ions cannot be ruled out as a determinant of W`.

Exercise training permits specific energy systems to be isolated in order to examine how they contribute to the power: time-to-exhaustion relationship. Jenkins and Quigley (29) used prior sprint exercise training (exhaustion induced ~ 60 seconds) and found that critical power was unaffected (234 W vs. 242 W) while W` was significantly increased (13.4 kJ vs. 20.0 kJ) which supported previous findings from the same authors (31). In another study by Jenkins and Quigley (30), aerobic training at critical power increased critical power (196 W vs. 255 W) without changing W` (19.9 kJ vs. 14.7 kJ) (N.B. authors had poor statistical power with which to assess this difference). Gaesser et al. (17) utilized two separate training protocols, with one group performing interval training at 100% $\dot{V}O_{2max}$ and another group exercising at 50% $\dot{V}O_{2max}$.

Both groups increased critical power with no difference between the groups, while W` was unaffected by both types of training. Recently, the effects of respiratory muscle training have been examined to see if respiratory muscle fatigue contributes to the power: time-to-exhaustion relationship (33). It was found that inspiratory muscle training had no effect on critical power (264 W vs. 263 W) but significantly increased W` (24.8 kJ vs. 29.0 kJ).

Prior exercise provides another method of manipulating physiological responses to determine how the parameters are affected. Miura et al. (41) used prior heavy (below critical power) exercise to alter the power: time-to-exhaustion relationship. Six minutes of prior exercise at 50% Δ (halfway between gas exchange threshold and critical power) increased critical power (169 W vs. 177 W) while W` was unaltered (11.0 kJ vs. 11.0 kJ). Ferguson et al. (12) examined prior severe (above critical power) exercise and found a decrease in W` (16.1 kJ vs. 10.6 kJ) while critical power was unaltered (241 W vs. 242 W). Vanhatalo et al. (57) used prior sprint exercise and found that critical power was unaffected, but W` was significantly lower. The increase in critical power following prior heavy exercise was attributed to an increased aerobic component speculated to occur as a result of increased blood flow to the exercising muscles (41). The lowering of W` with prior sprint exercise was attributed to a reduction in the intramuscular PCr concentration available for energy production. Thus, severe intensity exercise alters W` while leaving the critical power unaltered, while heavy exercise enhances critical power with no effect on W`.

Pedal frequency has been demonstrated to alter the power: time-to-exhaustion relationship, with critical power at 100 rpm significantly lower than critical power at 60 rpm (8, 23). Using this, Barker et al. (2) determined critical power and W` at 100 rpm and 60 rpm. In addition an eight minute ride at each pedal-rate-specific critical power was utilized to determine the oxygen cost for both. Critical power was lower for 100 rpm than 60 rpm as a work rate while W` was unaffected by pedal rate. However, the $\dot{V}O_2$ at critical power was not different between the pedal frequencies. This study suggests that critical power is a metabolic rate as it occurred at the same $\dot{V}O_2$ despite different work rates.

The Velocity: Time-to-Exhaustion Relationship

The majority of the research in the literature and therefore presented in this study was collected using the power: time-to-exhaustion relationship. However, the findings regarding the power: time-to-exhaustion relationship translates well to the velocity: time-to-exhaustion relationship (22). Hughson et al. (28) first demonstrated that the hyperbolic relationship applies to running, with velocity replacing power and distance replacing work. This relationship is determined in much the same manner as the power: time-to-exhaustion relationship (27, 28, 46).

Typically, an initial protocol is completed to determine $\dot{V}O_{2peak}$ as well as the velocity at $\dot{V}O_{2peak}$ (V_{peak}). V_{peak} is then used to calculate velocities spanning ~90 – 120% V_{peak} at which the constant velocity runs take place. The subject completes four to six of these constant velocity runs and the data is then fit with the 1/time and velocity-time models for the determination of critical velocity and D`.

The velocity: time-to-exhaustion relationship is modeled in the same manner as the power: time-to-exhaustion relationship. The hyperbolic function between velocity and time-to-exhaustion yields the non-linear model:

$t = D` / (V – CV)$ **(Equation 7)**

and linear model:

$V = (D`/ t) + CV$ **(Equation 8)**

where *V* is velocity, *t* is time-to-exhaustion, *CV* is critical velocity, and *D`* represents a finite distance that can be covered above CV. In this relationship critical velocity represents a velocity that can be maintained for long periods of time and D` represents the distance that can be covered above critical velocity. Distance is used in place of work due to the difficult nature of determining the work of running.

Significance of the Power/Velocity: Time-to-Exhaustion Relationship

The power/velocity: time-to-exhaustion relationship can be used to determine the fastest time within which a person can run a given distance. In theory, at this determined speed the D` would be fully exhausted upon crossing the finish line allowing for the maximum contribution of energy stores determining D` and critical velocity. Mathematical modeling has suggested that running at this predetermined velocity would produce the fastest possible time for that subject

and deviating from this speed at any point will produce slower times (15). In this regard, critical velocity and D` have significant implications on how a person will fare in a race.

Critical power and velocity have also been compared with other measures of sustainable performance such as the maximal lactate steady-state (MLSS). MLSS is the highest intensity for which blood lactate concentration is able to achieve a steady-state (4, 5). The definitions of critical power and MLSS would imply that both measurements represent the same intensity, however critical power has been demonstrated to occur at slightly but significantly higher power outputs than MLSS (10, 50). With critical velocity the results differ in that no difference between critical velocity and the velocity at MLSS has been found (52). Therefore it is inconclusive as to whether MLSS and critical power/velocity represent the same intensity of exercise which determine the maximal rate of sustainable performance.

Limitations of the Power/Velocity: Time-to-Exhaustion Relationship

The power: time-to-exhaustion relationship has some limitations and assumptions. Several assumptions are made when describing the relationship with a two-parameter hyperbolic model. Specifically, the relationship suggests that there is an infinite amount of power that can be produced as time approaches zero. This is not possible as eventually the muscles will not be able to generate enough force to move the pedals. At the other end of the relationship, the hyperbolic model suggests that time-to-exhaustion is unlimited at power outputs equivalent to critical power. These assumptions are also present in the velocity: time-to-exhaustion relationship. The model suggests that there is a velocity that can be maintained indefinitely as well as an infinite velocity that can be achieved momentarily. However, as previously mentioned this is not the case as time-to-exhaustion is limited to within an approximate range of 16 – 60 minutes at critical power/velocity. In addition to the modeling assumptions, the determination of critical power/velocity is dependent upon the effort put forth by the subject. All of the tests are performed to exhaustion and thus are dependent upon the subject putting out maximal effort each time. Therefore, if a subject retires from a test prior to reaching true exhaustion it will alter the resulting values of critical power/velocity and W/D`. If these limitations are taken into account, accuracy can be increased in the parameter estimates.

Another limitation with determining these relationships is the number of tests they require. Requiring multiple testing sessions to determine the power/velocity: time-to-exhaustion relationship is time consuming for intervention studies in which the relationship must be determined under separate conditions, requiring a minimum of nine testing sessions per subject (2, 17, 23, 29, 38-41, 48). In addition, the need for multiple visits to the lab makes the test unpractical for use either in the athletic or clinical setting. This issue has been resolved for the power: time-to-exhaustion relationship as the single 3-minute all-out cycle test can be used to determine critical power and W`. A similar time-saving approach to determine critical velocity has not been explored. As a result, the practical use of the velocity: time-to-exhaustion relationship in a variety of settings is limited. Therefore, we were interested in determining if a single test can be utilized to determine the parameters of the velocity: time-to-exhaustion relationship.

Chapter 3 - Methods

Subjects

Eleven healthy subjects (6 men & 5 women, mean ± SD; age 24.9 ± 3.1 years, body mass 68.4 ± 11.9 kg, height 173.3 ± 9.8 cm) volunteered to participate in this study and provided written informed consent. The study was approved by the Institutional Review Board of Kansas State University, Manhattan, KS. Prior to testing, subjects were informed of the overall protocol, along with the potential risks and benefits involved. Subjects were instructed to abstain from vigorous activity for 24 hours prior to testing and not to consume caffeine three hours prior to testing. Each subject reported to the Human Exercise Physiology Laboratory a minimum of six times with at least 24 hours between testing sessions. The data for one subject was unusable due to missing data during the 3-minute field test. As a result a final number of ten subjects were used for data analysis. Within these ten subjects eight completed an additional three tests to establish the reproducibility of the 3-minute running protocol and define a 95% confidence interval around the 1/time model CV.

Calibration

Prior to testing, the treadmill (Quinton Brute Q55XT Sport, Bothell, WA, USA) was calibrated across the expected velocities for the running sessions. Pulmonary gas exchange ($\dot{V}O_2$, expired carbon dioxide ($\dot{V}CO_2$), and ventilation ($\dot{V}_E$)) were measured breath-by-breath during the incremental test, $\dot{V}O_{2max}$ validation test, and the runs at +/- 95% confidence interval CV using a metabolic measurement system (Cardio2, Medical Graphics Corp., St. Paul, MN,USA). Prior to each testing session, the system was calibrated using gases of known concentration spanning the expected range of expired gases. The volume signal was calibrated with a syringe of known volume (3.0 l).

Incremental Test to Volitional Exhaustion

The incremental protocol used for the determination of maximal oxygen consumption ($\dot{V}O_{2max}$) and the velocity at $\dot{V}O_{2max}$ (V_{peak}) was adapted from Smith & Jones (52). The protocol began with an initial velocity of $8 - 10$ km·h^{-1} (depending upon the reported level of fitness from the subject) at a fixed incline of 1%. The velocity was increased by 0.5 km·h^{-1} every three

minutes until the subject achieved 95% estimated maximal heart rate (220 – age). At this point, the velocity was reduced by 1 km·h^{-1} and the treadmill grade was increased 1% every 60 seconds until volitional exhaustion. Oxygen consumption ($\dot{V}O_2$) and velocity were averaged over the final minute of each three minute stage leading up to 95% maximal heart rate. Velocity was plotted against $\dot{V}O_2$ and linearly extrapolated to V_{peak} at the subject's $\dot{V}O_{2max}$. Validation of $\dot{V}O_{2max}$ was accomplished during a subsequent 110% V_{peak} critical velocity run. $\dot{V}O_{2max}$ was considered valid if the highest $\dot{V}O_2$ obtained on the secondary test was less than 0.2 L greater than that on the incremental max test (49, 51). If a difference was observed (occurred 3 times within this study), a second validation test was completed at ~ 120% and V_{peak} was adjusted accordingly.

Traditional Determination of the Velocity: Time-to-Exhaustion Relationship

For the determination of CV, each subject completed at least four randomly ordered constant velocity runs to exhaustion typically spanning 80 – 120% V_{peak} designed to induce exhaustion within 2 – 15 minutes   These runs took place on a treadmill set at a grade of 1%, previously demonstrated to most accurately reflect outdoor running (34). Subjects initiated each testing session with a warm-up at a velocity of 5 km·h^{-1} for 5 minutes. After this warm-up, the subject straddled the treadmill belt as it was brought up to the correct velocity. At that time, the subjects used a handrail to lower themselves onto the moving belt. The elapsed time of each test was recorded to the nearest second from when the subject stepped onto the treadmill belt until the time when the subject grasped the handrail, signaling exhaustion. Throughout these tests, investigators provided strong verbal encouragement to minimize exercise termination prior to exhaustion. The resulting time-to-exhaustion data was then fit to the two-parameter hyperbolic model using both the velocity-time and 1/time functions (Equation 3 & 4) to determine CV & D`.

Validation of Critical Velocity Measurement

Using the 1/time model, a 95% confidence interval was constructed around each subject's CV. Subjects then completed one run each at the (+) and (-) 95% confidence interval velocity with the same protocol as for the previous constant velocity tests. The subjects ran to exhaustion or 15 minutes (when the test was terminated). Intensities just above and below CP have

previously been determined with the use of a 95% confidence interval in conjunction with the linear model (35). If the elicited $\dot{V}O_2$ response achieves steady-state below CV, but continually rises above CV, these responses imply the boundary between the heavy and severe domains is within this interval, and that CV thus lies somewhere between these two intensities. The 95% confidence interval provides a narrow range of velocities for these two runs, thus allowing for more confidence to be placed in the CV measurement.

Single Test for the Determination of the Velocity: Time-to-Exhaustion Relationship

For the 3-minute test, subjects began by warming-up on a track with light jogging and walking at velocities that would not begin to utilize D` (below CV). The test was initiated from a stationary position and the subjects were instructed to maintain maximal effort throughout the entire test even though velocity would decline after achieving initial peak values. Strong verbal encouragement was provided throughout the test to prevent pacing. The end-test velocity (EV) was determined using the average velocity over the last 30 seconds of the 3-minute run, while the accumulative distance above end-test velocity (DEV) was determined from the area under the velocity curve above EV (see below). Eight subjects completed a second 3-minute test to determine the reproducibility of the protocol. Inherent within the velocity-time relationship, the utilization or accumulation of too much D` is not possible (i.e. a subject cannot cover too much distance), however the utilization of less than maximal D` is possible as a result of pacing; therefore, the test with the largest DEV was used for data analysis. The subject's velocity during all tests was recorded second-by-second using an accelerometer positioned on the right foot (RS800CX, Polar Electro Inc., NY, USA). The accelerometer was calibrated for each subject to the manufacturer's specifications using the data from the constant-velocity runs on the treadmill.

Data Analysis

The breath-by-breath data collected during the incremental $\dot{V}O_{2max}$ test was first converted into 15 second intervals and time-aligned to the start of incremental exercise for data analysis. $\dot{V}O_{2max}$ was defined as the highest 15 second value from the incremental test and was validated as previously mentioned. The breath-by-breath data were then converted into 30 second averages and used in the plot of velocity vs. $\dot{V}O_2$ for determination of V_{peak}. The data from the constant velocity runs was analyzed using the velocity-time model (Equation 3) and the

1/time model (Equation 4) for the determination of CV and D`. Heart rate was monitored beat-by-beat during all tests with a heart rate monitor (RS800CX, Polar Electro Inc., NY, USA).

Statistical Analyses

Comparisons of parameters among the velocity-time model, 1/time model, and 3-minute test were made using a one-way ANOVA with repeated measures with Tukey's post-hoc analysis. Parameter comparisons between the first and second 3-minute test, as well as the comparison of the above and below CV runs, were made using paired t-tests. Pearson product moment correlations were used to examine test-retest reliability for the two 3-minute tests, as well as the relationships among the three models (velocity-time, 1/time, and 3-minute). Statistical significance was accepted at a level of $P < 0.05$ and the results are presented as mean $\pm$ SD.

Chapter 4 - Results

Incremental Ramp Test

Individual data for $\dot{V}O_{2max}$ and V_{peak} from the incremental ramp test are presented in Table 1, with group mean values of $3.30 \pm 0.70 \, l \cdot min^{-1}$ and $15.0 \pm 2.2 \, km \cdot h^{-1}$, respectively.

Velocity: Time-to-Exhaustion Relationship

The time-to-exhaustion during constant velocity runs typically ranged between 170 – 890 seconds. The parameters determined using the 1/time and velocity-time models from these four runs are presented in Table 2. A good linear fit was displayed for all subjects, with an average r^2 = 0.96 ± 0.02. Statistical significances were detected between the velocity-time and 1/time models when comparing CV (P < 0.05) and D` (P < 0.05). The 1/time and velocity-time models for the average CV represented 85.3 ± 8.1% and 81.7 ± 7.7% $V_{peak}$, respectively. Figure 1 demonstrates the use of these two models for an individual subject in determining CV and D`.

3-minute Test

The individual and group mean data for the 3-minute tests are presented in Table 2, while Figure 2 depicts a representative 3-minute test. In the eight of the ten subjects in whom two 3-minute tests were conducted, no significant difference was observed between the two tests for a group mean for either EV (13.8 $km \cdot h^{-1}$ and 13.6 $km \cdot h^{-1}$; P = 0.634) or DEV (126 m and 126 m), while the reliability coefficient was 0.85 for EV and 0.32 for DEV (Figure 3). Thus EV demonstrated high reproducibility for the 3-minute test. With no significant difference detected between the two 3-minute tests, the data from the two subjects who only completed one 3-mintue test were included for subsequent analysis. The average 3-minute EV was not significantly different from the 1/time model CV, but was significantly higher than the velocity-time model CV (P = 0.002). The EV was on average 87.4 ± 10.2% V_{peak}. There was no significant difference between the DEV and the 1/time model D`; however, DEV was significantly smaller than the velocity-time model D` (P = 0.002). Relationships among the parameters of the three models are presented in Figure 4 and Figure 5. There was a significant inverse relationship (r^2 = -0.30; P = 0.002) between CV and D` as well as EV and DEV for all three methods of parameter estimation (Figure 6).

Run Above and Run Below CV

Figure 7 and Figure 8 depict a representative subject's $\dot{V}O_2$ data and the group mean $\dot{V}O_2$ data for the runs above and below CV, respectively. All runs took place at intensities, on average, $8.8 \pm 3.1\%$ above and below CV (i.e. mean velocities of 13.9 and 11.7 km·h^{-1}, respectively). Subjects achieved a significantly higher $\dot{V}O_2$ for the run above CV (3.3 ± 0.6 l·min^{-1}) compared to the run below CV (2.8 ± 0.6 l·min^{-1}; $P < 0.05$). The run above CV resulted in a significantly higher percentage of $\dot{V}O_{2max}$ being attained ($95.2\% \pm 4.0$) than the run below CV ($84.5\% \pm 3.5$; $P < 0.05$), however the $\dot{V}O_2$ obtained in the run above CV was significantly lower than $\dot{V}O_{2max}$ ($P = 0.017$). During the run above CV, no subject was able to complete 15 minutes of running, with an average time to exhaustion of 643 ± 213 s. However, during the run below CV every subject was able to complete 15 minutes of running, leading to a significantly longer duration for this test ($P = 0.011$). Throughout the run below CV, $\dot{V}O_2$ was not different from 180 s to 900 s, indicating that $\dot{V}O_2$ was able to attain steady-state while $\dot{V}O_2$ did not achieve steady-state for the run above CV as seen by the significant difference in $\dot{V}O_2$ between 180 s to the termination of exercise ($P = 0.01$) (Figure 8).

Chapter 5 - Discussion

To our knowledge this is the first study to utilize a single exercise test for the determination of the velocity: time-to-exhaustion relationship parameters. The major finding of the present study, consistent with our first hypothesis is that the 3-minute all-out running test is accurate in determining CV. However, inconsistent with our second hypothesis, the 3-minute all-out running test DEV underestimated D`.

CV is the running equivalent to CP, therefore physiological information regarding CP may be applied to the CV relationship as well. CP and CV both occur around $80 - 89\%$ $\dot{V}O_{2peak}$ in the general population (3, 10, 47, 52) and the time to exhaustion at CP/CV ranges between 16 – 60 minutes depending upon the mathematical model used (3, 6, 7, 9, 25, 32, 37). This duration is in disagreement with the implication of the hyperbolic asymptote of the velocity: time-to-exhaustion theory, which states that CV can be maintained for an indefinite period of time without fatigue. Nevertheless, the velocity: time-to-exhaustion relationship is a major determinant and predictor of endurance performance (14, 15, 25), as it defines the body's maximum ability to achieve steady-state for $\dot{V}O_2,$ pH, Pi, and PCr. In support of this, CV has been shown to occur in proximity to maximal lactate steady-state (MLSS) (52). Thus, CV and MLSS represent a threshold above which exercise duration is severely limited and can be predicted based upon the CV and D` parameters. The 3-minute running test, in theory, should allow for easier determination of CV. In the present study the 3-minute all-out running test EV was equivalent to the 1/time model CV, but it overestimated the velocity-time model CV (Table 2; Figure 4). Importantly, each subject completed runs at +/- the 95% confidence interval around CV. The fact that steady-state $\dot{V}O_2$ was achieved and every subject completed 15 minutes of exercise below CV, while steady-state was not achieved and exercise duration was markedly limited above CV (Figure 8) validates that CV lay within this confidence interval, as it represents the threshold above which steady-state for $\dot{V}O_2$ is no longer attainable (47). Importantly, the 3-minute all-out running test EV as well as the velocity-time CV both fell within this 95% confidence interval, suggesting any physiologically relevant difference among the estimates may be minimal despite the statistical difference (Figure 9).

Consistent with previous reports (30, 54, 56), in the present study CV and D` demonstrated an inverse relationship (Figure 6), i.e., subjects with a high CV had, on average, a low D` and subjects with a low CV on average had a high D`. This relationship held true irrespective of the model or mode used to determine the parameters (1/time model, velocity-time model, and 3-minute test). The mechanistic underpinning of the inverse relationship remains to be identified.

The use of ^{31}P-MRS technology has allowed researchers to examine the intramuscular physiological changes that occur with knee-extension exercise above and below CP. Below CP steady-state levels of PCr, Pi, pH can be achieved in the muscle, while continuous changes occur above CP until exhaustion (35). Building upon this, Vanhatalo et al. (56) demonstrated that for exercise at different work rates in the severe domain, at exhaustion PCr, pH, and Pi achieved similar concentrations despite occurring at different work rates. These findings suggest that a critical concentration might exist for these compounds which reflect the utilization of W` (and presumably D`). In contrast, Ferguson et al. (11) have recently shown that following exhaustive exercise, $\dot{V}O_2$ recovered prior to W` restoration, while arterial lactate was still elevated after W` restoration. The authors interpreted this finding as suggesting that W` is not solely determined by PCr stores, arterial lactate, or a depletable finite energy store in isolation.

Previous investigations examining the 3-minute all-out critical power test found a progressive decrease in muscle activation throughout the test (59). Specifically, at the initial high power outputs, presumably all available motor units would be recruited, but as type II fibers fatigued, muscle activation declined throughout as measured by electromyogram. However, $\dot{V}O_2$ remained elevated providing a "slow-component like" response (59). A similar response would be expected to occur in the present study with the 3-minute sprint on the track, i.e., the initial velocity would recruit all available motor units, but as type II fibers fatigued, muscle activation would be predicted to decrease in parallel with the decline in velocity.

According to the velocity: time-to-exhaustion model, D` is utilized at intensities greater than CV until that velocity is no longer sustainable. The duration that this exercise can be maintained is dependent upon the magnitude of D`, which is determined by available energy stores and their depletion (35, 42, 43), as well as the accumulation of fatigue-inducing metabolites (11, 35). In accordance with this, the 3-minute test should deplete these stores and

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accumulate the metabolites, and the distance required to do so should be equivalent to D`.
However, in the present study DEV underestimated D` from both models by 31.4 and 47.0%,
despite only being significantly different from the velocity-time model (Table 2; Figure 5). DEV
also exhibited higher intrasubject variability than EV when the test was repeated a second time,
despite no difference in the group mean value. A possible explanation for this discrepancy
between DEV and D` may lie in the difference between the treadmill and the track. With
propulsion forward on the track, air resistance is present, producing a higher metabolic demand
as opposed to running on a treadmill. However, a 1% grade on the treadmill was utilized to
address this issue (34). Running on the track, the subject will also encounter turns which may
have altered the subject's velocity. However, close analysis of the accelerometer data does not
support this, as velocity was well maintained through the turns. Motivation may have altered the
DEV measure as the 3-minute running test is dependent upon the maximal sustained effort put
forth by the subject. If the subject does not maintain maximal effort throughout the test this
would result in an underestimation of DEV compared to D`, as was seen in the current study.
Irrespective of the cause, it appears that the subjects did not utilize D` in its entirety which led to
a lower DEV than predicted. A similar finding has been observed for cycle ergometry, where
W` during the 3-minute all-out test underestimates W` from the traditional approach (55).
Further research is needed to investigate this discrepancy between DEV and D`.

The velocity-time and 1/time models used to calculate CV and D` in the present study
differed significantly in the resulting parameter estimates by 3.9 and 22.8%, respectively, as
previously reported in the literature (7, 16, 26). The cause of this discrepancy between models is
found in the effect on the variance of defining the independent and dependent variables. For the
velocity-time model the dependent and independent variables are correctly assigned as time and
velocity, respectively (i.e., velocity was held constant). In reversing this assignment for the
1/time model, the least squares analysis adjusts the error in velocity instead of time. The
difference in defining the variables can result in different parameter values despite utilizing the
same data. However, it has also been demonstrated that if the correlation coefficient for the
1/time model is greater than 0.94 (0.98 in present study) reversing the independent and
dependent variables has no significant effect on the parameter estimates for that data set (48).
Nonetheless differences between the models can still occur (16). Even though differences have
been reported, high between-model correlations suggest that the models are indeed measuring

the same parameters (16). In the literature some studies have reported parameters for both models (2, 23, 35, 39-41, 45, 47, 48) while others report only the parameters determined using the 1/time model (6, 11, 12, 14, 50, 54, 55). Using the 95% confidence interval in the current study allows for increased confidence that the "true" CV is within this range. In fact, CV from both the velocity-time and 1/time models, as well as EV, fell within the 95% confidence interval.

The availability of a single test for the determination of CV allows for a more practical use of CV. Specifically, this methodology for intervention studies will reduce the number of testing sessions utilized, thus decreasing the time requirement for both subject and investigator. In addition to facilitating the use of CV in research settings, a single test presents a more practical test for the athletic arena. Considering that all Olympic endurance events are won at intensities around CV ($\sim 85\%$ $\dot{V}O_{2peak}$) (36), a simple test for determining CV could be advantageous for an athlete or coach. In theory, the exercise duration that can be maintained at a specific velocity can be determined using the equation [t=D`/ (V-CV)] or [t = DEV/ (V-EV)], however the underestimation of D` by DEV would lead to inaccurate prediction times. For example using the group mean values, a subject would be predicted to run for 360 s with the 1/time model, 380 s with the velocity-time model, and 272 s from the 3-minute test. If this problem is resolved, in theory a runner's best time can be determined for any given distance. This has been demonstrated with the use of modeling procedures to show that if any part of a race is run below the predicted velocity from the velocity: time-to-exhaustion relationship the time can never be recovered compared to running the entire race at that velocity (15).

Based on the findings of the current study, several compelling future research ideas have risen. One such idea is to determine the cause for the underestimation of D` with the 3-minute test. As mentioned previously, this would enhance the usefulness of the 3-minute running test. Another research avenue is to utilize the 3-minute running test in collegiate middle distance runners in order to determine if these parameters can, in practice, predict an athlete's fastest time for a given distance. Future studies might also examine the effect a specific intervention has on the parameters of the 3-minute running test.

In summary, the EV determined from the 3-minute all-out running test was not significantly different from the 1/time model CV. Despite the accurate determination of CV, D` was underestimated by DEV from this test. The exact cause for this underestimation currently is not known and further research is needed to address this issue. Use of the all-out exercise test on

the cycle ergometer developed by Vanhatalo et al. (55) thus can be extended to running for the determination of CV using a 3-minute all-out test.

Subject	$\dot{V}O_{2peak}$ (l·min^{-1})	$\dot{V}O_2$ validation (l·min^{-1})	$\dot{V}O_{2max}$ (l·min^{-1})	$\dot{V}O_{2max}$ (ml·kg^{-1}·min^{-1})	V_{peak} (km·h^{-1})
1	2.56	2.60	2.60	44.4	13.7
2	2.71	2.90	2.90	51.2	16.3
3	3.60	3.38	3.60	46.0	12.6
4	3.71	3.64	3.71	48.6	15.9
5	4.10	3.92	4.10	45.1	13.3
6	4.39	4.49	4.49	61.0	20.3
7	2.71	2.74	2.74	50.8	13.5
8	3.57	3.41	3.57	48.5	15.4
9	2.97	2.95	2.97	48.8	14.4
10	2.30	2.35	2.35	38.2	14.3
Mean	3.26	3.24	3.30	48.3	15.0
SD	0.71	0.67	0.70	5.9	2.2

Table 1. Individual incremental ramp test data.

Subject	CV 1/time (km·h^{-1})	D` 1/time (meters)	CV velocity-time (km·h^{-1})	D` velocity-time (meters)	EV 3-min (km·h^{-1})	DEV 3-min (meters)
1	11.9	146	11.3	223	11.9	169
2	13.1	221	12.7	282	13.1	142
3	9.8	467	9.9	538	10.3	144
4	12.9	183	12.6	237	12.7	138
5	11.8	353	11.7	373	12.4	197
6	18.6	84	17.8	183	19.2	80
7	11.2	214	11.1	228	12.3	124
8	12.9	200	12.5	256	13.6	127
9	14.9	128	13.8	199	15.2	143
10	10.8	205	9.7	329	9.5	248
Mean	12.8*	220[+]	12.3	285	13.0[#]	151[#]
SD	2.5	112	2.4	106	2.7	45

Table 2. Velocity-time parameters determined using the 1/time, velocity-time, and 3-minute models. CV = critical velocity, D` = finite distance, EV = end-test velocity, DEV = distance above end-test velocity. Significantly different from the velocity-time model at * $P<0.05$, [#] $P=0.002$, [+] $P<0.001$.
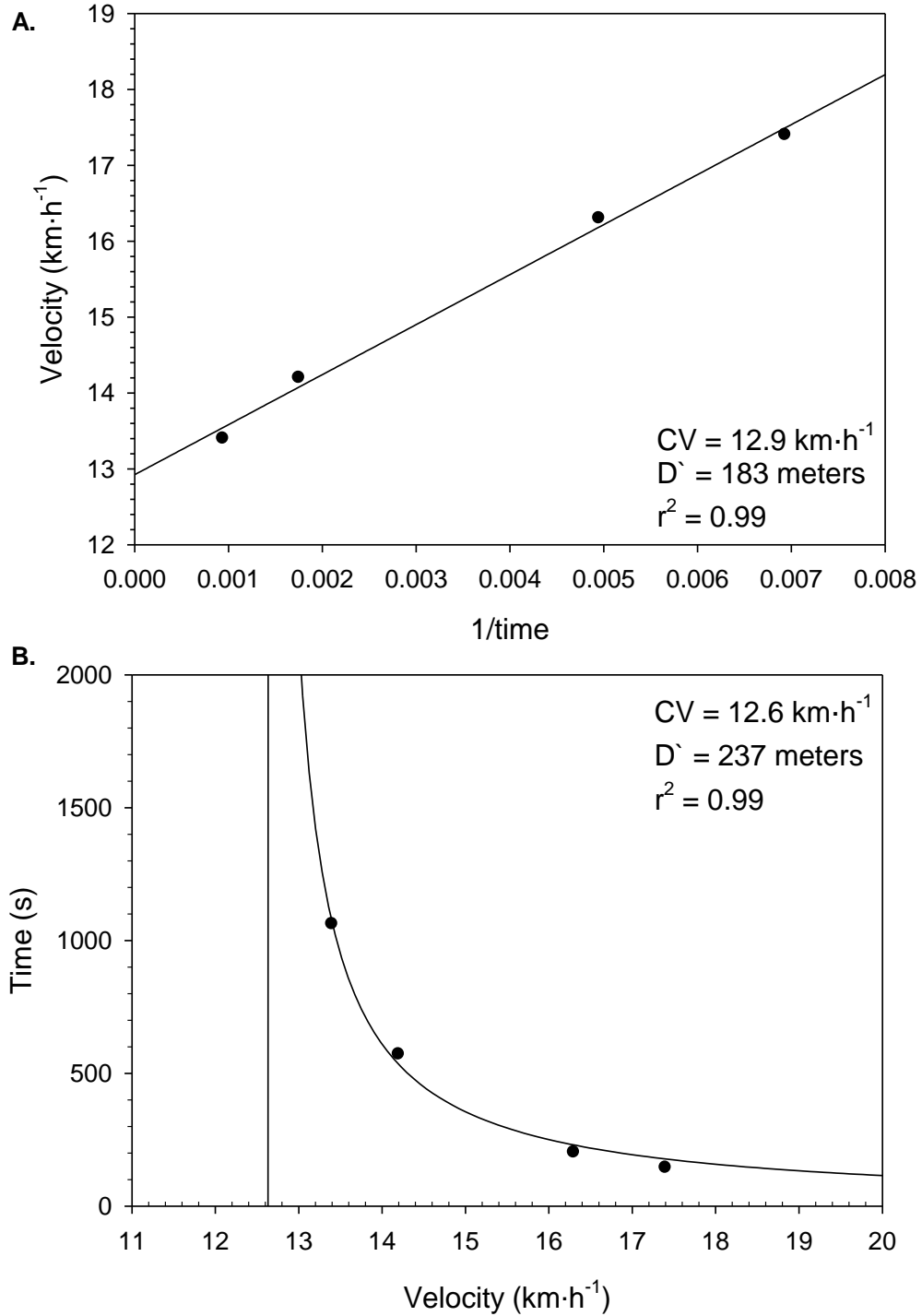
Figure 1. Critical velocity and D` estimation for a representative subject.
A. Linear 1/time model. CV determined from y-intercept and D` determined from slope. B. Non-linear velocity-time model. CV determined from vertical asymptote and D` determined from curvature constant.
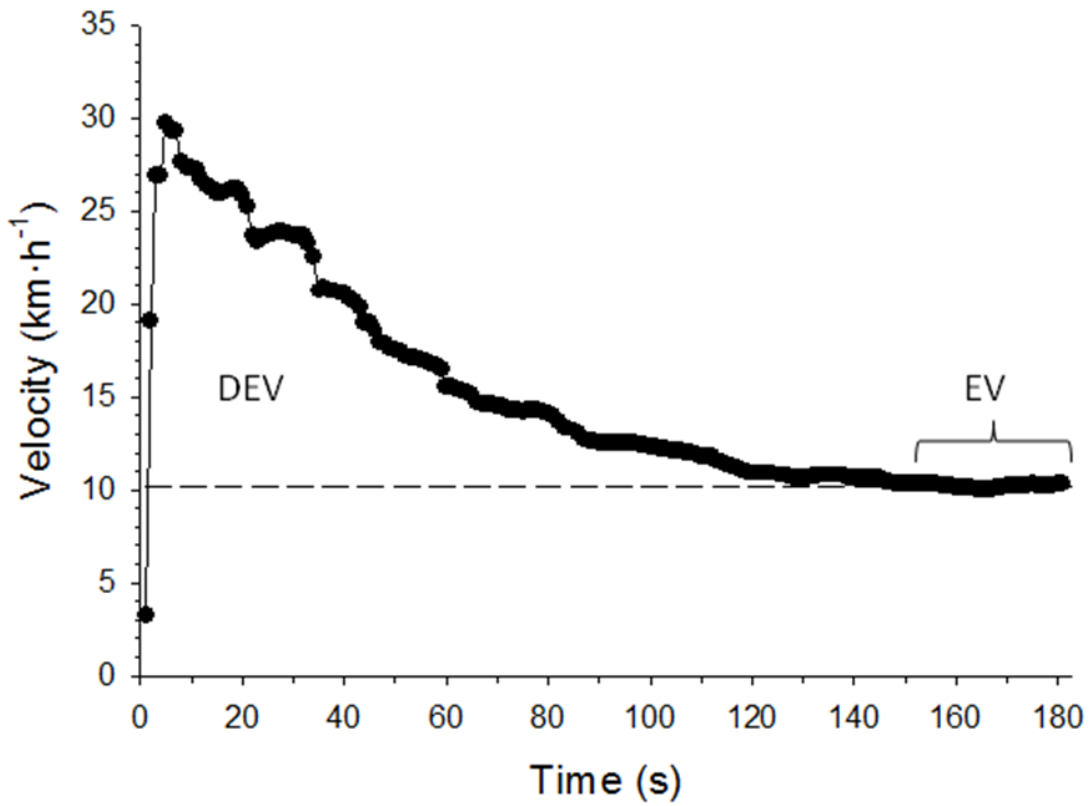
Figure 2. A representative 3-minute test. Second-by-second velocity data with the last 30 seconds being averaged as end-test velocity (EV) and the area under the curve representing the work (as distance) done above end-test velocity (DEV).
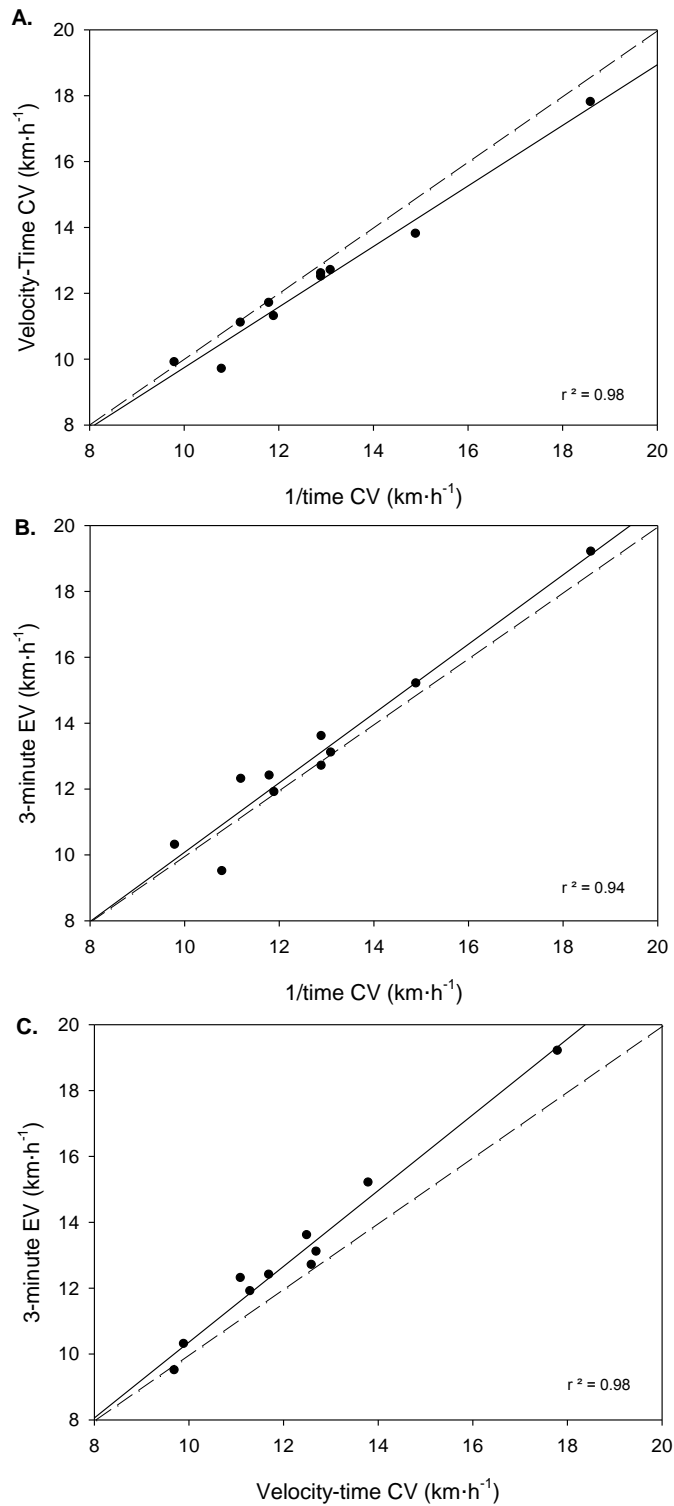
Figure 3. Graphical comparison between the first and second 3-minute tests.
A. Individual and mean response for EV with a reliability coefficient = 0.85. B. Individual and mean results for DEV with a reliability coefficient = 0.32. No difference was found between the group mean EV or DEV between the two tests.

Figure 4. Correlations between CV and EV. A. Velocity-time model CV vs. 1/time model CV B. 3-minute end-test velocity (EV) vs. 1/time model CV. C. 3-minute EV vs. velocity-time model CV. Line of identity shown as dashed line.

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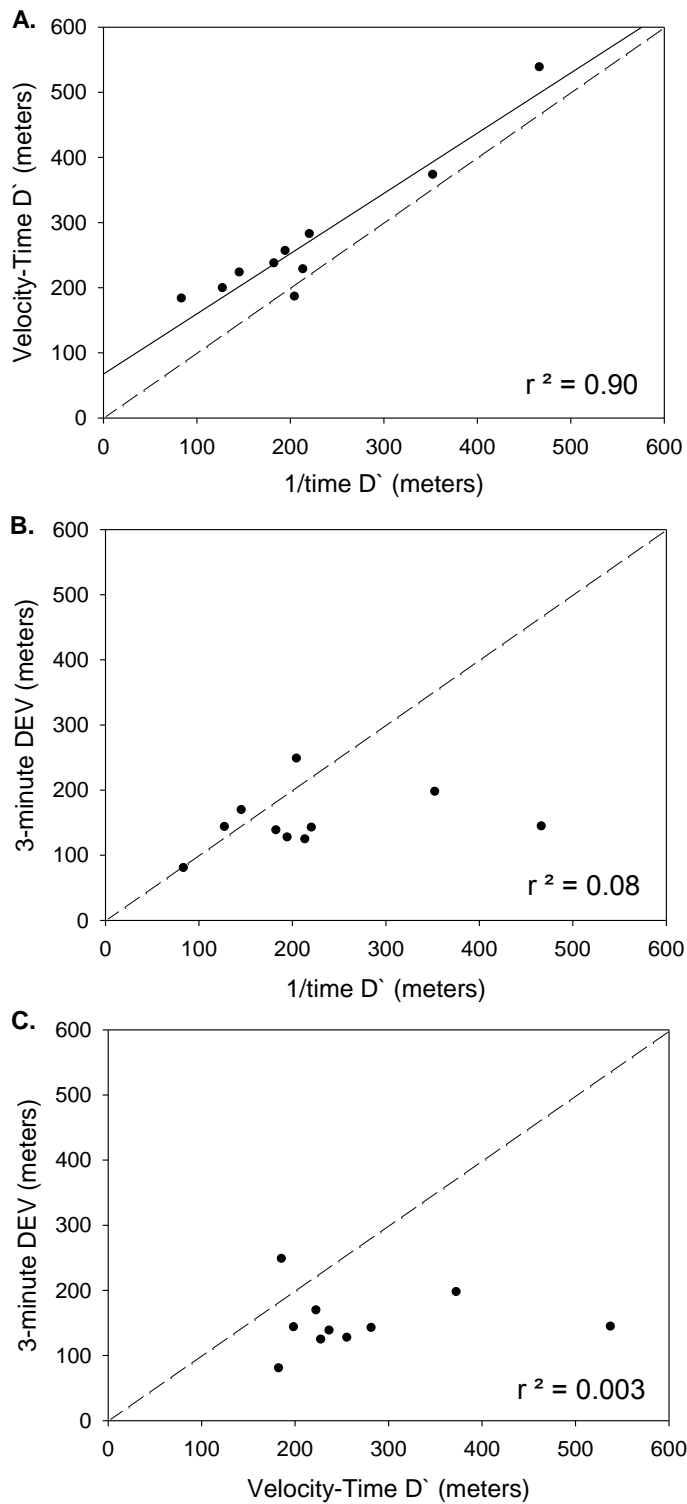**Figure 5. Correlations between W` and DEV.** A. Velocity-time D` vs. 1/time D`. B. 3-min distance above end-test velocity (DEV) vs. 1/time D`. C. 3-min DEV vs. velocity-time D`. Line of identity shown as dashed line.
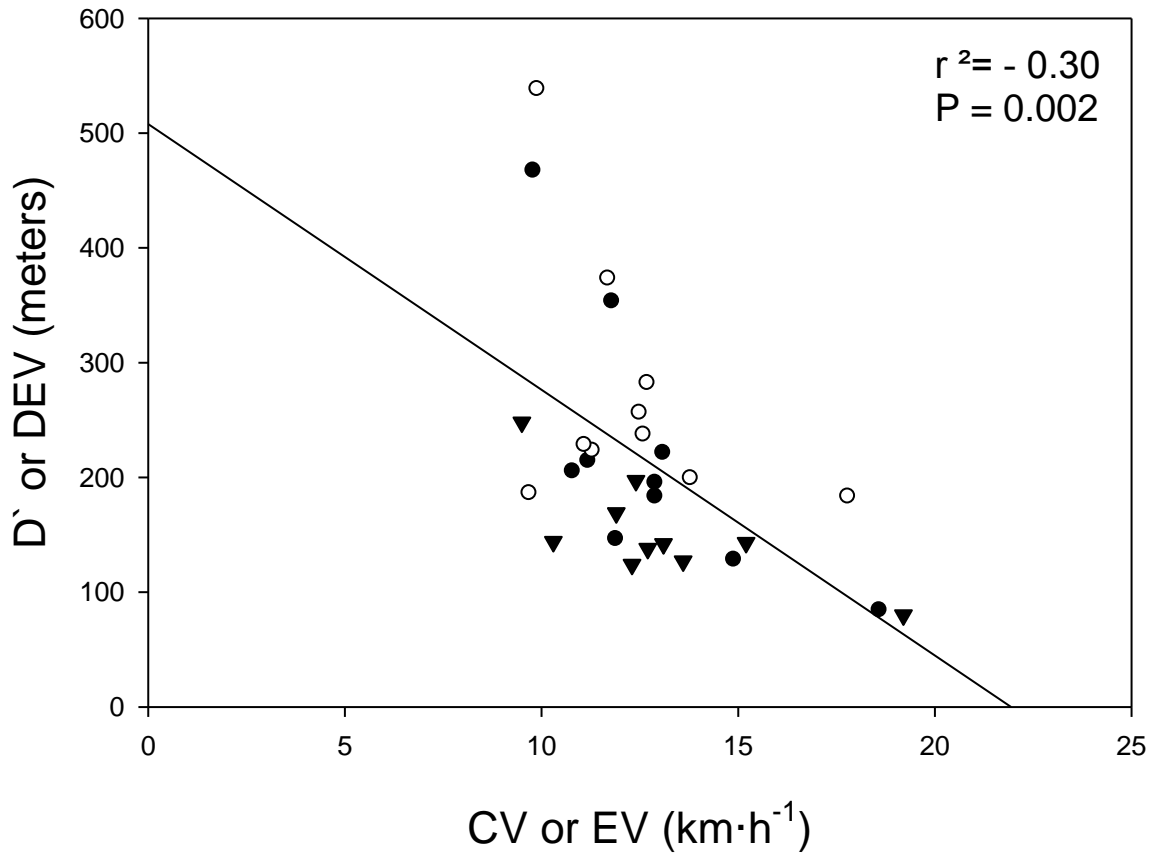
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Figure 6. Inverse relationship between D` and CV or DEV and EV. An inverse relationship exists independent of the model used to determine the parameters. (●) = 1/time model, (○) = velocity-time model, (▼) = 3-minute test
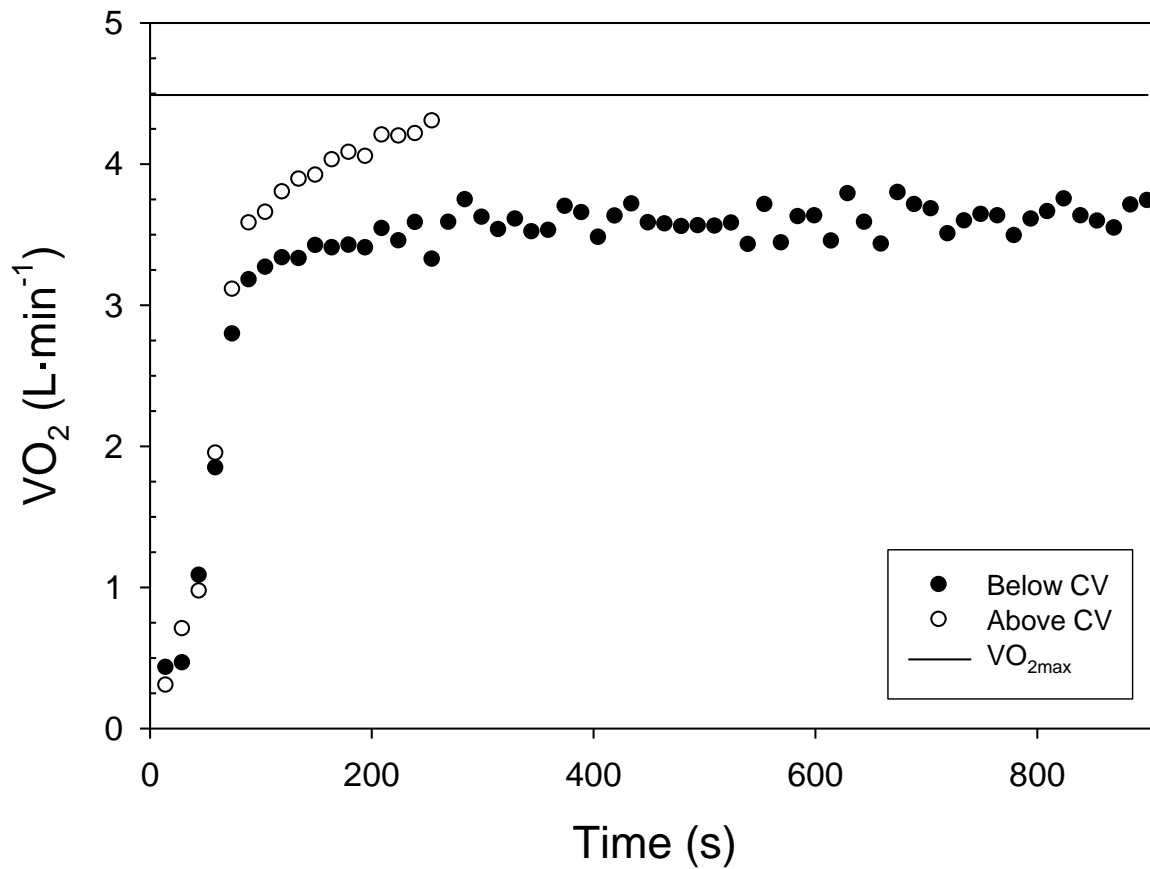
Figure 7. Representative data for the +/- 95% confidence interval CV runs. Subject ran for the entire 15 minutes during the run below critical velocity (CV) at 16.9 km·h^{-1}, but could not complete 15 minutes for the run above CV at 20.4 km·h^{-1}. Results were characteristic of the group.
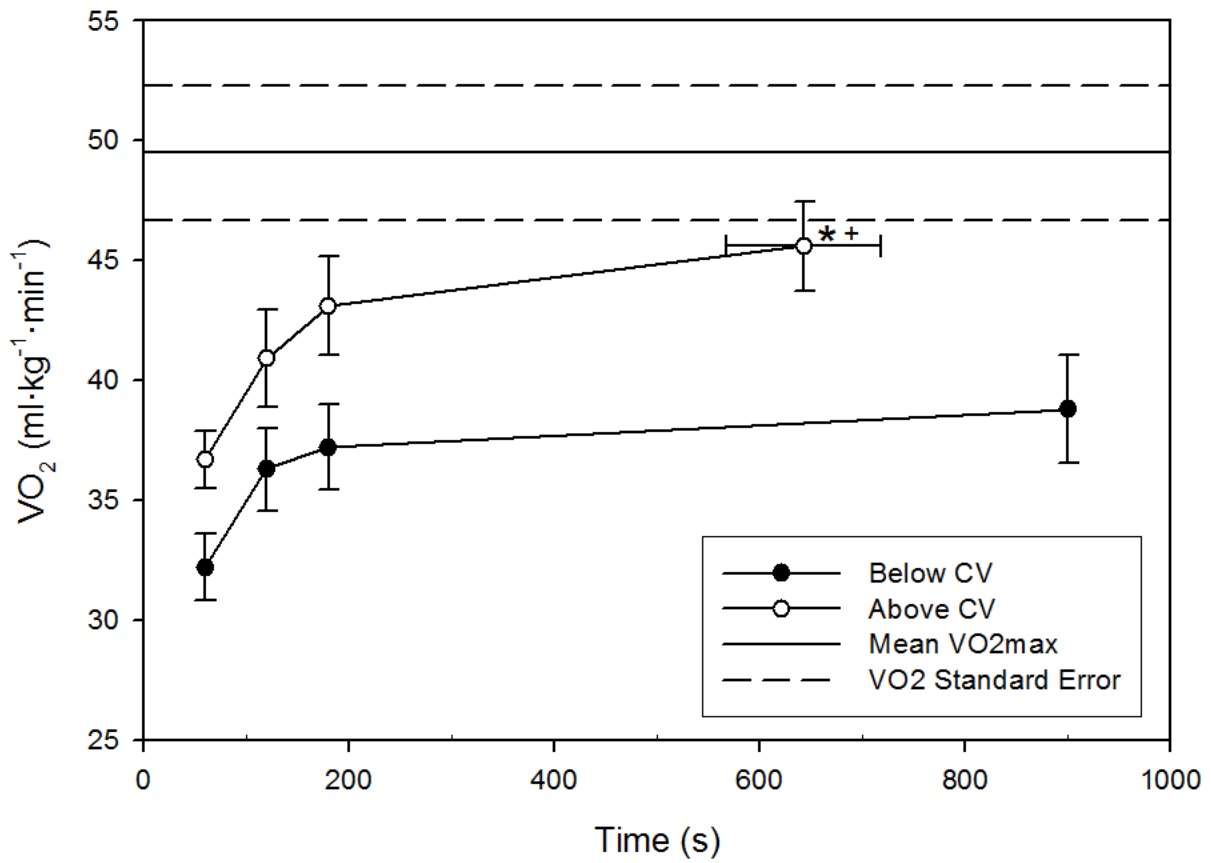
Figure 8. Group mean oxygen uptake response for +/- 95% confidence interval runs.

* significantly greater than the corresponding $\dot{V}O_2$ value at 180 seconds (P = 0.010).

+ significantly greater than end-exercise value for below CV run $\dot{V}O_2$ (P < 0.001).
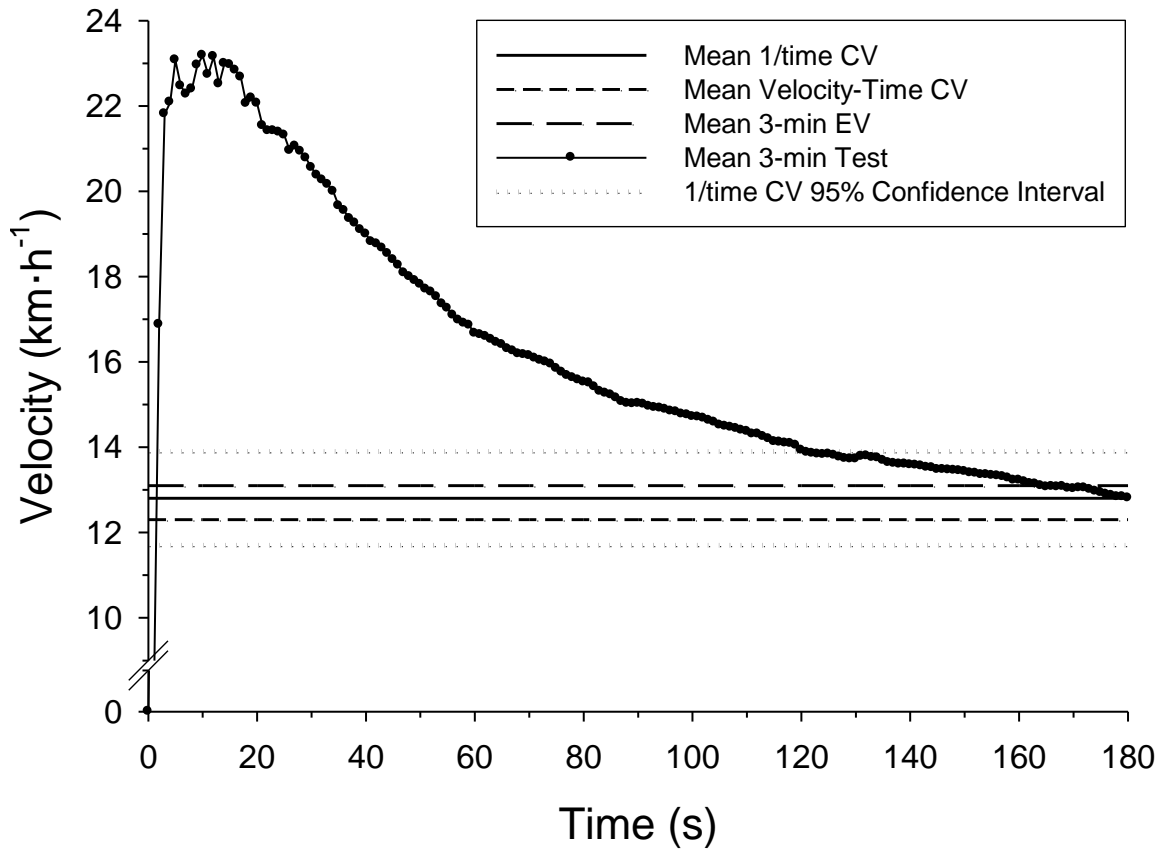
Figure 9. Group mean velocity during 3-minute test compared to traditional determinants of critical velocity (1/time & velocity-time) with the mean 95% confidence interval determined from the 1/time model. Critical velocity (CV) for velocity-time model was significantly lower than 1/time model CV and 3-min end-test velocity (EV), $P < 0.05$. For standard deviation values refer to Table 2.

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