A Non Exercise Based Estimation of the Critical Velocity and Anaerobic Distance Capacity in Collegiate Swimmers

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Dr. Heather Erwin, Director of Graduate Studies
A NON EXERCISE BASED ESTIMATION OF THE CRITICAL VELOCITY AND ANAEROBIC DISTANCE CAPACITY IN COLLEGIATE SWIMMERS

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the College of Education at the University of Kentucky

By

Howard Henry Brim III

Lexington, Kentucky

Director: Dr. Haley Bergstrom, Assistant Professor of Kinesiology & Health Promotion

Lexington, Kentucky

2016
This study determined if the parameters of the critical velocity (CV) model could be obtained from estimated performance times at various swimming distances. Fourteen collegiate swimmers provided their actual fastest long-course times ($AT_{com}$) at standard distances and inquired completion times ($IT_{com}$) at non-standard distances. The total distance (TD) versus $AT_{com}$ and $IT_{com}$ relationships were used to estimate the parameters of the CV model. Inquiry-estimated times to completion ($IET_{com}$) for the 100, 200, 400, and 800 m were derived using the CV ($CV_{inq}$) and anaerobic distance capacity ($ADC_{inq}$) estimates from the TD versus $IT_{com}$ relationship in the equation: $IET_{com} = \frac{ADC_{inq}}{(V-CV_{inq})}$.

Significant relationships and no mean differences were observed between the actual and inquired parameters of CV and ADC. At 100 meters, $AT_{com}$ was significantly faster than $IET_{com}$, while no mean differences were observed at 200, 400, and 800 meters. No significant relationships between the $AT_{com}$ and $IET_{com}$ were observed at any distances. Significant intra-individual variability was observed in the $IET_{com}$, compared with the $AT_{com}$. These findings indicated that the parameters of the CV model can be derived from self-reported performance estimations in elite swimmers, however, the model did not accurately predict individual performance times.
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<td>AT&lt;sub&gt;com&lt;/sub&gt;</td>
<td>Actual time to completion</td>
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<tr>
<td>ADC/ AWC</td>
<td>Anaerobic distance capacity/ Anaerobic work capacity</td>
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<tr>
<td>T&lt;sub&gt;lim&lt;/sub&gt;</td>
<td>Time to exhaustion</td>
</tr>
<tr>
<td>TD</td>
<td>Total distance</td>
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<tr>
<td>W&lt;sub&gt;lim&lt;/sub&gt;</td>
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Chapter I: Introduction

The critical power (CP) and critical force tests, originally proposed by Monod and Scherrer (30) describe the linear relationship between the total work performed ($W_{lim}$) and time to exhaustion ($T_{lim}$) for local muscle groups during intermittent isometric and dynamic muscle actions. Moritani et al. (31), applied the CP concept to cycle ergometry. For this test, the $W_{lim}$ was plotted against the $T_{lim}$ for a series of 3 to 4 constant power output work bouts. The $W_{lim}$ versus $T_{lim}$ relationship provides estimates of two separate parameters, the CP and anaerobic work capacity (AWC). The CP represents the slope of the $W_{lim}$ versus $T_{lim}$ relationship and the AWC is the y-intercept described by the equation: $W_{lim}=AWC + CP \cdot T_{lim}$ (Figure 1.1).

It has been suggested (30) that the CP represents the maximum power output that can be maintained for an extended period of time, and the AWC represents the total amount of work that can be performed above CP using energy sources stored within the muscle (i.e. Phosphocreatine, adenosine triphosphate (ATP), glycogen, and oxygen already bound to myoglobin). In addition, the CP is the asymptote of the hyperbolic relationship between power output and $T_{lim}$. The $T_{lim}$ at any power ($P$) output above CP can be predicted from this hyperbolic relationship. The equation for the estimation of $T_{lim}$ was derived as follows:

$W_{lim}=P(T_{lim})$ and $W_{lim}=AWC + CP \cdot T_{lim}$

Thus, $P(T_{lim})=AWC + CP \cdot T_{lim}$ and $T_{lim}=\frac{AWC}{P-CP}$ (Figure 1.1)

The CP model has since been applied to a number of different exercise modes, including running (21), rowing (27), and swimming (39). In addition to expanding the adaptability of the CP model, a number of studies have modified the CP/CV test in an
attempt to improve the practicality of the application of the model (11,19,35). Housh et al. (19) demonstrated that accurate estimates of the CP and the AWC can be achieved from two work bouts, when the work bout duration ranges from 1 to 10 min and the resulting times to completion are separated by at least 5 min.

Typically, the parameters of the CP/CV test are determined from a series of constant work rate tests performed to exhaustion to derive the $W_{\text{lim}}$ or TD and $T_{\text{lim}}$. Previous studies (7), however, have suggested the use of performance trials may be a more appropriate method for determining the parameters of the CP/CV model and predicting the $T_{\text{lim}}$ of exercise performed at intensities greater than the CP or CV. One of the initial applications of the CV model to swimming (40), used set distances of 50, 100, 200 and 400m plotted against $T_{\text{lim}}$ and the CV and AWC were derived from the TD versus $T_{\text{lim}}$ relationship.

Many coaches, trainers, and athletes, however may not be willing to take time away from training to complete a series of performance tests. A method for determining the parameters of the CV model based on estimated performance times would be beneficial to swimmers because it would allow for the measurement of improvements throughout the season without the need to add performance trials to an athlete's strict training routine. In general, collegiate swimmers have competed for several years in their discipline and their experience should allow them to accurately estimate their finishing times at specific distances. No previous studies, however, have examined the validity of the CV and AWC parameter derived from estimated performance capabilities at predetermined distance during high-intensity swimming trials. Therefore, the purpose of this study is to determine if the parameters of the CV model can be obtained from
estimates of performance times at various distances. We hypothesize that the swimmers will accurately estimate their performance capabilities and that the CV and AWC parameters can be derived from a non-exercise based estimation.
Figure 1.1. (Top): The linear relationship between the total work performed ($W_{lim}$) and the time to exhaustion ($T_{lim}$). The equation $W_{lim} = a + b (T_{lim})$ describes the $W_{lim}$ versus $T_{lim}$ relationship where (b) represent the critical power (CP), and (a) represents the amount of work that can be performed above CP using only stored energy from anaerobic pathways.

(Bottom): The hyperbolic relationship between cycle ergometry power output ($P$) and the time to exhaustion ($T_{lim}$). The equation $T_{lim} = \frac{AWC}{P-CP}$ describes how $T_{lim}$ at any $P$ above the CP can be predicted from this relationship.
Chapter II: Review of Literature

1. Development of the Critical Power Concept


The purpose of this study was to examine the work capacity of four local muscle groups (biceps brachii, flexor digitorum superficialis, quadriceps femoris, triceps brachii) during intermittent isometric and dynamic muscle actions. To evaluate this, three different constant power output (P) exercise tests to exhaustion were performed. Exhaustion was defined as the point where P could no longer be maintained. The total amount of work (or limit work; $W_{\text{lim}}$) was calculated as the product of the power output and the time to exhaustion ($T_{\text{lim}}$) ($W_{\text{lim}} = P \times T_{\text{lim}}$). A mathematical model was used to linearly relate $W_{\text{lim}}$ and $T_{\text{lim}}$ and was described by the equation, $W_{\text{lim}} = a + b(T_{\text{lim}})$. The results of the dynamic work capacity test demonstrated a linear relationship between the $W_{\text{lim}}$ and $T_{\text{lim}}$. Three parameters were identified from this mathematical model: 1) Critical power (CP), which was the slope of the $W_{\text{lim}}$ versus $T_{\text{lim}}$ relationship, and defined as “...the maximum rate a muscle group can keep up for a very long time without fatigue.” (p. 329); 2) anaerobic work capacity (AWC) defined as the total amount of work that could be performed above CP using stored energy sources within the active muscles and independent of oxygen supply; and 3) $T_{\text{lim}}$ for any $P$ greater than the CP $T_{\text{lim}} = \frac{a}{P-b}$. 


The purposes of this study were to; 1) apply the critical power (CP) concept to a total-body work model; and 2) assess the relationships among CP, the anaerobic threshold (AT), and $\dot{V}O_2$ max. Eight male and eight female college students volunteered for this study. An electrically-braked cycle ergometer was utilized during each test. $\dot{V}O_2$ max and the AT were determined from an incremental cycling protocol and gas exchange measurements. The CP test required the subjects perform four different power outputs specific to each gender. The power outputs for the males were 400, 350, 300, and 275 W, while the females performed power outputs of 300, 250, 200, and 175 W. The power output remained constant throughout the test and the pedal cadence was set between 60-70 rev·min$^{-1}$. The total work ($W_{lim}$) was plotted against time to exhaustion ($T_{lim}$). The CP was defined as the slope and anaerobic work capacity (AWC) the y-intercept of the $W_{lim}$ versus $T_{lim}$ relationship, and was described by the linear regression equation $W_{lim} = a + b (T_{lim})$. There was a significant linear relationship between $W_{lim}$ and $T_{lim}$ ($r = 0.982-0.998$, $p<0.01$). Significant relationships were also observed among the $\dot{V}O_2$ and power output associated with the CP, AT, and $\dot{V}O_2$ max ($r=0.87-0.92$, p.0.01). The authors concluded that: 1) The $W_{lim}$ versus $T_{lim}$ relationship was highly linear; 2) CP is the slope of the relationship between $W_{lim}$ and $T_{lim}$, and is dependent on oxygen supply; 3) a regression equation can be derived ($\dot{V}O_2$ max$ = 0.00795 \times [CP+AWC] + 0.114$) to estimate $\dot{V}O_2$ max from CP and AWC; and 4) CP is the asymptote of the hyperbolic relationship between
power output and $T_{\text{lim}}$. Furthermore, the hyperbolic relationship between power output and $T_{\text{lim}}$ allows the $T_{\text{lim}}$ to be predicted for any power output greater than CP. The equation for the estimation of $T_{\text{lim}}$ was derived as follows:

$$W_{\text{lim}} = P(T_{\text{lim}})$$

$$W_{\text{lim}} = AWC + CP \cdot (T_{\text{lim}})$$

Thus, $P(T_{\text{lim}}) = AWC + CP \cdot (T_{\text{lim}})$ and $T_{\text{lim}} = \frac{AWC}{P-CP}$

**Summary**

This section focused on the origins of the critical power (CP) concept and its initial application to total body exercise (Monod and Scherrer, 1965; Mortani et al., 1981). The CP concept was proposed by Monod and Scherrer (1965), to examine the work performed by local (less than one-third of the whole muscle mass) muscle groups during intermittent isometric and dynamic muscle actions. The authors (Monod and Scherrer, 1965) used three different exhaustive power outputs (P), to examine the relationship between the total work performed ($W_{\text{lim}}$) and times to exhaustion ($T_{\text{lim}}$). The $W_{\text{lim}}$ versus $T_{\text{lim}}$ was highly linear and the slope of this relationship was termed the CP, while the y-intercept was termed the anaerobic work capacity (AWC) (Monod & Scherrer 1965). The CP was defined as “… the maximum rate a muscle group can keep up for a very long time without fatigue.” (p. 329). The authors (Monod & Scherrer 1965) concluded that, theoretically, exhaustion would not occur for any imposed P of an active local muscle group that was less than or equal to CP.

Mortani et al. (1981) applied the CP concept to total body cycle ergometry and examined the physiological significance of CP by determining its relationship to the anaerobic threshold (AT) and $\dot{V}O_2 \text{max}$. Four, constant P cycle ergometry work bouts
were performed to exhaustion to determine CP and AWC from the \( W_{\text{lim}} \) versus \( T_{\text{lim}} \) relationship. There was a highly linear relationship between \( W_{\text{lim}} \) and \( T_{\text{lim}} \), as well as significant correlations among the CP, AT, and \( \dot{V}O_2 \) max (Moritani et al. 1981). The authors (Moritani et al. 1981) concluded that the CP concept was applicable to total body exercise, the CP was related to oxygen supply, and the AWC was the total amount of work performed above CP.

These findings (Monod and Scherrer 1965; Moritani et al. 1981) provided the basis for the development of an individually derived exercise intensity that could be used to examine both aerobic and anaerobic capabilities from a single test. Furthermore, it was suggested (Monod & Scherrer 1965 and Moritani et al. 1981) that the CP concept could be used to predict performance at any intensity greater than CP. Thus, the development of the CP concept allowed for a new, individually-derived threshold that could be used to examine exercise performance.

2. Application of the Critical Power concept to other modes of exercise


The purpose of this study was to apply the critical power (CP) concept to treadmill running to derive a critical running velocity (CV). Six male cross-country runners (age= 19-22 yr.) completed a graded exercise test to exhaustion to determine \( \dot{V}O_2 \) max. The CV test required subjects to run at six different velocities at intensities high enough to result in exhaustion within 2-12 minutes. The velocity remained constant throughout each test and the time to exhaustion (\( T_{\text{lim}} \)) was recorded. The treadmill
velocity was plotted against the inverse of $T_{lim}$ ($1/T_{lim}$) and was described by the equation $V = AWC(1/T_{lim}) + CP$, where $AWC$ = anaerobic work capacity and $CV$ = critical velocity. A significant linear relationship was observed between running velocity and $1/T_{lim}$ for all subjects ($r = 0.979 - 0.997$). Significant relationships were also observed between $CV$ and $\dot{V}O_2 \text{max}$ ($r = 0.84$, $p < 0.05$) and between time predicted from the velocity versus $T_{lim}$ relationship and actual time during a 10,000m race ($r = 0.67$, $p < 0.05$). The predicted times were observed to be 2-3 minutes faster than the actual race times. It was concluded that high speed treadmill running versus time to exhaustion does conform to the hyperbolic model of power versus time for cycle ergometry. In addition, running velocity is linearly related to the inverse $T_{lim}$. Thus, the authors applied the CP concept for cycle ergometry to treadmill running.


The purposes of this study were to: 1) apply the critical power model for cycle ergometry to simulated rowing, to derive a critical rowing velocity (CV); 2) compare multiple CV estimates produced by four different distances and three mathematical models and; 3) assess the accuracy of these CV estimates to predict 2,000-m velocity during a simulated rowing race. 16 experienced male rowers (age= 22.7± 3.9 yr.) participated in this study. A Concept II Model C rowing machine was utilized to perform all tests. Assessment of $\dot{V}O_2 \text{max}$ was conducted using an incremental rowing protocol and the measurement of gas exchange parameters. Subjects performed trials at six different distances (200, 400, 600, 800, 1000, and 1200m). The trial distances were then
combined in three groups of four distances each (short, medium, and long distance) and a final group consisting of all six distances. Three different CV mathematical models were used, including the: 1) linear distance-time model, 2) linear velocity/time model, and 3) Nonlinear velocity-time model. This resulted in a total of 12 different CV estimates for each subject. The results indicated no significant difference in CV and 2000-m rowing velocity. The linear distance-time model using all six distances produced the most accurate estimates of actual 2000-m velocity. There was a significant relationship between CV and VO2 max (r=0.91, p< 0.05), CV and the mean velocity during the 2000m simulated rowing race (r=0.97, p< 0.05), and between VO2 max and simulated 2000m rowing race velocity (r=0.93, p< 0.05). The authors concluded that: 1) the CV estimation accurately predicted actual 2000m simulated rowing performance; 2) The medium distances and four to six trials using the linear distance-time model resulted in the most accurate estimate of actual 2000-m rowing performance, and 3) the nonlinear velocity-time model resulted in the most conservative estimations of CV.


The purpose of this study was to apply the critical power concept for cycle ergometry to swimming to derive a critical swimming velocity (CV). Nine experienced male swimmers (18-21 yr.) performed six constant velocity swimming trials and an incremental exercise assessment using a swimming flume. The CV test required subjects
to swim at six constant velocities (V) between 1.2- 1.7 m·sec\(^{-1}\). The velocities were chosen at intensities that could be maintained for a minimum of 5 minutes and time to exhaustion (T\(_{lim}\)) was recorded for each bout. The swimming distance (D\(_{lim}\)) was determined by the equation (D\(_{lim}\) = v \times T\(_{lim}\)), and was plotted against T\(_{lim}\). The results indicated a strong linear relationship between D\(_{lim}\) and T\(_{lim}\), for each swimmer (r\(^2\) > 0.998, P< 0.01). A significant relationship was also reported between CV and mean 400 meter velocity (r = 0.864, P < 0.01). The authors concluded that the CP concept was applicable to swimming.

**Summary**

This section focused on the application of the critical power (CP) concept to different modes of exercise including; running, rowing, and swimming (Hughson et al. 1984; Kennedy et al. 2000; Wakayoshi et al. 1992). Hughson et al. (1984) showed that treadmill running velocity and time to exhaustion (T\(_{lim}\)) formed a hyperbolic relationship similar to the power output versus T\(_{lim}\) relationship during cycle ergometry. The authors (Hughson et al. 1984) reported a highly linear relationship between the treadmill velocity and the inverse of time (1/T\(_{lim}\)). The y-intercept of the velocity- T\(_{lim}\) relationship was termed the critical velocity (CV), analogous to CP during cycle ergometry, and defined as the maximum running velocity that could be maintained for an extended period of time without fatigue. The authors (Hughson et al. 1984) reported a significant relationship between running velocity and 1/T\(_{lim}\), CV and \(\dot{V}O_2\) max, as well as predicted time from the CP model and actual time to complete a 10,000 m race. The authors concluded that the CP model for cycle ergometry could be applied to treadmill running.

The CP model was applied by Kennedy et al. (2000) to simulated rowing performance, to derive a critical rowing velocity (CV). Six distances were divided into
three groups of four, and an additional group of all six distances. CV was determined by using three separate mathematical models. The results indicated no significant difference between CV and actual 2000-m rowing velocity. Strong significant relationships were reported (Kennedy et al. 2000) between CV and $\dot{V}O_2$ max, CV and mean 2000-m rowing velocity, and $\dot{V}O_2$ max and actual 2000-m rowing velocity. In addition, the CV estimation accurately predicted actual 2000-m simulated rowing performance. Thus, the authors concluded that the CP model for cycle ergometry could be applied to rowing to derived a critical rowing velocity.

The CP concept developed by Moritani et al. (1981) was applied to swimming by Wakayoshi et al. (1992) to derive a critical swimming velocity (CV). CV was determined using constant velocity swimming trials at swimming intensities that could be maintained for a minimum of 5 minutes. Swimming distance ($D_{lim}$) was determined from the equation: $D_{lim} = v \times T_{lim}$, and was plotted against time to exhaustion ($T_{lim}$). The results indicated a strong linear relationship between $D_{lim}$ and $T_{lim}$, and between CV and mean 400 meter velocity. From these data, the authors (Wakayoshi et al. 1992) concluded that the CP concept can be applied to swimming.

3. Parameters of the Critical Power and Critical Velocity Test

I. Critical Power (CP) and Critical Velocity (CV)


The purpose of this study was to investigate the metabolic and respiratory patterns of responses during, constant-load cycle ergometry at and above the critical power (CP).
Eight healthy males (19-24 yr.) performed a minimum of six exhaustive cycle ergometry work bouts consisting of an incremental test and at least five square-wave endurance exercise tests (SWEETs). The incremental exercise test was performed to determine \( \dot{V}O_2 \) peak, maximal power output (P max), and the lactate threshold. The SWEETs were performed to estimate CP. The power outputs (P) for the tests were chosen at intensities that could be maintained for a minimum of 1 min and time to exhaustion (T_{lim}) was recorded for each trial. The P was plotted against 1/T_{lim}, and the anaerobic work capacity (AWC) and critical power (CP) were the slope and the y-intercept, respectively, and were defined by the equation: P= AWC/time + CP. Two additional SWEETs were performed at intensities equal to the CP and CP + 5% of P max. These tests continued for 24 minutes or until exhaustion occurred. Blood was sampled for levels of lactate, pyruvate, norepinephrine, and pH. The results of the CP test indicated that CP was significantly greater than lactate threshold in all subjects. The SWEET performed at CP was continued for the entire 24 minute duration and steady state \( \dot{V}O_2 \) was attained within 12-20 minutes for all subjects. The SWEET performed at CP + 5% of P max resulted in exhaustion in less than 24 minutes for all but one subject.

The \( \dot{V}O_2 \) results at CP + 5% of P max indicated that the subjects did not attain steady state and end-test \( \dot{V}O_2 \) levels were recorded at or around \( \dot{V}O_2 \) max. The authors concluded that: 1) during constant-load exercise at an intensity greater than CP, \( \dot{V}O_2 \) will continue to increase until \( \dot{V}O_2 \) max and limit work are achieved; 2) the mechanisms associated with lactate metabolism appear to be the dominant mediators of the failure of \( \dot{V}O_2 \) to attain steady state during exercise above CP; and 3) CP is the highest power output where \( \dot{V}O_2 \) and blood lactate reach steady state values.
The purposes of this study were to: 1) assess the validity of critical power (CP) as a measure of endurance ability; 2) determine if 8 weeks of endurance training at or near CP would increase the slope, but not the y-intercept of the CP function; and 3) to examine whether an increase in CP would result in the ability to sustain a higher exercise intensity post-training. Eighteen active males (19.1 ± 0.8 yr.) using cycle ergometry, performed a VO$_2$ max test, CP assessment, and an additional 40-minute work bout at or near CP. The CP assessment consisted of three constant-load work bouts performed to exhaustion at intensities of 270, 330, and 390 watts, at a pedal cadence of 60 rev·min$^{-1}$. Work bouts were administered in ascending order of intensity and were separated by a minimum of 3 hours. The 40 min work bout at or near CP took place on a separate day and blood lactate was sampled throughout the test to monitor the lactate plateau. The power output was adjusted up or down during the 40-min work bout so that the subject could maintain exercise. The mean power output for the 40-min test was determined. Twelve subjects were then randomly chosen to undergo a training intervention that was 8 weeks in duration. The training intervention consisted of 30 minutes of cycling, three times a week. The cycling duration increased by 5 minutes following the 5$^{th}$ week and by an additional 5 minutes (40 min total) during the 8$^{th}$ week. The initial training intensity was set at each subject's respective mean power output during the first 40-min work bout and subjects were allowed to increase the workload, if they desired. Following the 8 week training program, subjects performed a second VO$_2$ max test, CP assessment, and 40-min work bout. The increase in both VO$_2$ max and CP was significantly higher in the training group.
than in the control group (p < 0.01). Mean CP, power output, and \( \dot{V}O_2 \) max increased by 30%, 28%, and 8%, respectively, in the training group. For the training group, a significant increase in CP was observed post-training (p < 0.05). A significant relationship was observed between CP and \( \dot{V}O_2 \) max before and after training (r = 0.61, 0.77, respectfully, p <0.01). Significant relationships were also observed between mean power output during the 40-minute work bout and CP both before and after training (r = 0.87-0.95, p <0.01) and the training group between the increase in mean power output and the increase in CP (r = 0.89, p <0.01). No significant relationship was observed between the increase in mean power output and the increase in \( \dot{V}O_2 \) max. The authors concluded that: 1) there is a significant relationship between CP and aerobic capacity; and 2) endurance training enhances CP, without changing the y-intercept of the CP model.


The purpose of this study was to test the hypothesis that blood lactate, oxygen uptake (\( \dot{V}O_2 \)), and heart rate (HR) would attain steady-state during exercise conducted at critical power (CP). Seven trained males (23.4 ± 3.1 yts.) performed a \( \dot{V}O_2 \) max test, critical power (CP) assessment, and an additional test at CP, using a Monark cycle ergometer. The \( \dot{V}O_2 \) max test was an incremental ramp protocol and used to determine maximal minute power (MMP). The CP assessment consisted of three constant-load work bouts performed to exhaustion at intensities based on each subject's respective MMP. The work bout intensities were set at 120%, 100%, and 95% of MMP and were performed on separate days. A constant power output test at CP was performed to exhaustion, which
was determined as the inability to maintain the pre-set cadence for 5 s or more. Blood and expired air was sampled every 5 minutes, while HR was monitored continuously. Exercise at CP resulted in exhaustion in less than 40 minutes, for all but one subject. Significant differences over time were observed for $\dot{V}O_2$, HR, and blood lactate during exercise conducted at CP ($p< 0.001$). In addition, a significant relationship was reported between CP and time to exhaustion at CP ($r=0.92$, $p< 0.05$). The authors concluded that: 1) HR, $\dot{V}O_2$, and blood lactate do not attain steady state during exercise at CP; and 2) There is significant inter-individual variability with respect to the amount of time exercise at CP can be performed.


The purposes of this study were to: 1) test the hypothesis that $\dot{V}O_2$ max would be attained more rapidly at higher running velocities; 2) determine if the relationship between running intensity and time to achieve $\dot{V}O_2$ max ($T_{\text{max}}$) would fit a hyperbolic model; and 3) to compare critical velocity (CV) and CV', which was defined as the highest sub-maximal exercise intensity that can be sustained without eliciting $\dot{V}O_2$ max. Five males (33±7 yrs.) and 7 females (24±3 yrs.) performed five exhaustive treadmill work bouts in the form of an incremental exercise test and four constant velocity tests. The incremental exercise test allowed for the determination of $\dot{V}O_2$ max. The velocity at which $\dot{V}O_2$ max was first attained was defined as $V_{\text{max}}$. $V_{\text{max}}$ was used to determine the intensities for the constant velocity work bouts used to determine CV, which were set at 110%, 105%, 100%, and 95% of $V_{\text{max}}$. 
The time to reach $\dot{V}O_2\,_{\text{max}}$ was recorded for each of the constant-velocity tests. $CV'$ was determined from the relationship between velocity and $TT_{\text{max}}$. Estimates for $CV$ and the anaerobic work capacity (AWC) were determined using the equation: Velocity = \((\text{AWC}\cdot TTE^{-1}) + CV\), where TTE=time to exhaustion. Their derivatives $CV'$ and $AWC'$ were determined from the equation: Velocity = \((\text{AWC}'\cdot TT_{\text{max}}) + CV'\). The results indicated that TTE, $TT_{\text{max}}$, and time at $\dot{V}O_2\,_{\text{max}}$ were longer for the lower velocity tests. The mean CV was observed to be at 88% of $V_{\text{max}}$. The relationship between CV and $CV'$ was significant ($r = 0.97$, $P < 0.01$) and no significant mean difference was observed. The authors concluded that: 1) $\dot{V}O_2\,_{\text{max}}$ can be attained more rapidly at higher velocities; 2) The relationship between running velocity and $TT_{\text{max}}$ conforms to a hyperbolic model; and 3) CV represents the threshold velocity above which $\dot{V}O_2\,_{\text{max}}$ can be elicited during exercise of sufficient duration.

II. Anaerobic Work Capacity

Nebelsick-Gullett, Lori J., Terry J. Housh, Glen O. Johnson, and Sonja M. Bauge.

“A Comparison Between Methods of Measuring Anaerobic Work Capacity”


The purpose of this study was to examine the anaerobic work capacity (AWC) derived from the critical power model as an indirect measure of anaerobic capabilities. Twenty-five healthy females (1927 yrs.) performed a Wingate anaerobic test to assess anaerobic capacity and a critical power (CP) assessment using a Monark cycle ergometer. The Wingate test was performed against a resistance of 0.075 kg/ kg of body weight for thirty seconds and the total pedal revolutions were recorded. Anaerobic capacity (AC) was defined as the total work performed during the work bout and was determined with
the equation: \[ \text{Work (W)} = \left( \frac{\text{resistance (kg) \times 6 \times \# of revolutions} \times 2}{6 \cdot 12} \right) \]. The CP assessment consisted of three constant-load work bouts performed to exhaustion at intensities ranging from 156 to 313 watts, at a pedal cadence of \( 80 \text{ rev} \cdot \text{min}^{-1} \). The work bouts were administered in descending order of intensity and rest periods were sufficient to allow heart rate to return to within 5 beats per minute of pre-exercise value. A significant relationship was observed between AC from the Wingate test and AWC derived from the CP assessment \((r=0.74, p< 0.05)\). Significant relationships were also observed between AC and body weight \((r=0.77, p< 0.05)\), AWC and body weight \((r=0.64, p< 0.05)\), and between AC and AWC, independent of body weight \((r=0.51, p< 0.05)\). The authors concluded that the AWC determined from the CP test is a valid measure of anaerobic capabilities.


The purpose of this study was to assessed the validity of the anaerobic work capacity (AWC) derived from the critical power (CP) model in relation to data collected from five one-minute exercise bouts. Nine active males (18-21 yrs.) performed a \( \dot{V}O_2 \) max test, critical power (CP) assessment, and interval exercise bouts using a Monark cycle ergometer. The CP assessment consisted of three constant-load work bouts performed to exhaustion at intensities of 300, 350, and 400 watts, at a cadence of 60 \text{rev} \cdot \text{min}^{-1}. Rest periods of three hours were given between work bouts. The interval exercise consisted of five, 1 minute exercise bouts against a resistance of 0.075 N/ kg of body weight. The subjects were instructed to register the maximum number of pedal
revolutions as possible. Rest periods of five minutes were given between work bouts. Blood samples were taken during the rest periods and blood lactate and pH levels were evaluated. A significant relationship was observed between the AWC derived from the CP test and total work completed ($W_{\text{lim}}$) during the maximal interval exercise test ($r=0.74, p<0.05$). Significant relationships were also observed between post exercise venous blood pH and $T_{\text{lim}}$ ($r=0.92, p<0.01$) and between post-exercise venous blood pH and AWC ($r=0.92, p<0.01$). A weak, but significant relationship was observed between CP and AWC ($r=-0.11, p<0.05$). The authors concluded that: 1) AWC derived from the CP model was related to performance over five, 1 min maximal exercise bouts and thus is a valid indicator of the ability to perform intermittent, high intensity work; and 2) post-exercise venous blood pH was related to $T_{\text{lim}}$ during maximal interval exercise and to the AWC.


The purpose of this study was to compare the anaerobic work capacity (AWC) derived from the critical power (CP) model with two parameters obtained from a 90-s all-out test: 1) the amount of work performed above CP ($W_{90s}$); and 2) the anaerobic work capacity (AWC$_{90s}$). Ten males and four females performed a $\dot{V}O_2$ max test, a CP assessment, and two 90-s all-out test using an electrically-braked cycle ergometer. The $\dot{V}O_2$ max was determined from an incremental ramp protocol. The power output was plotted against the $\dot{V}O_2$ values from the incremental test and the regression equation derived was used to determine the power output associated with $\dot{V}O_2$ max (P-$\dot{V}O_2$ max).
The CP assessment consisted of three constant-load work bouts performed to exhaustion. Work bout intensities were set using percentages of the P-$\dot{V}O_2$ max at 103 ± 3%, 97 ± 3%, and 90 ± 2%. The time to exhaustion was recorded for each work bout and CP and AWC were determined using the two-parameter model. For the 90-s all-out test, subject pedaled at a self-selected isokinetic cadence (90 ± 3 rev·min$^{-1}$) for 90 seconds. The integral of the power output versus time relationship above CP was determined and was labeled $W_{90s}'$. The difference between power output derived from the P-$\dot{V}O_2$ max relationship and the actual power output obtained during the all-out 90-s test was used to determine the AWC$_{90s}$. No significant difference was observed between the AWC from the CP model and $W_{90s}'$ from the all-out test ($P=0.96, p < 0.05$). AWC$_{90s}$ was observed to be significantly greater than both AWC ($P=0.03, p < 0.05$) and $W_{90s}'$ ($P=0.04, p < 0.05$). Low levels of agreement were observed between AWC and AWC$_{90s}$ (37.6± 54.6 J·kg$^{-1}$), AWC and $W_{90s}'$ (4.4± 93.9 J·kg$^{-1}$), and between $W_{90s}'$ and AWC$_{90s}$ (33.2± 33.6 J·kg$^{-1}$). The authors concluded that: 1) since the AWC derived from the CP test and $W_{90s}'$ were the same, it provides support to the claim that the AWC is a constant value; and 2) low levels of agreement between AWC's derived from the CP test and from the 90-s all-out test suggests that they should not be used interchangeably to assess the AWC.

Summary

This section focused on the examination, and physiological significance of the two parameters of the critical power model: 1) the critical power (CP); and 2) the anaerobic work capacity. In the original CP model developed by Monod and Scherrer (1965), CP was defined as “... the maximum rate a muscle group can keep up for a very long time without fatigue.” (p. 329), and represents the slope relationship between of the
total work done (W_{lim}) and time to exhaustion (T_{lim}). Jenkins et al. (1992) examined the sensitivity of CP to reflect adaptation to endurance training. The results indicated a strong relationship between VO_{2 max} and CP, and, while VO_{2 max} did not increase significantly after training, CP and the mean power output that could be maintained during a 40 min work bout increased by 30% and 28%, respectfully. The authors concluded that there is a significant relationship between CP and aerobic capacity and endurance training enhances CP, without changing the y-intercept of the CP model.

Poole et al. (1988) examined the metabolic and respiratory responses to prolonged exercise at and above CP. The results indicated that CP was significantly greater than the lactate threshold, and at CP, VO_{2} attained steady-state within 12-20 minutes. The authors concluded that CP is the highest power output where VO_{2} and blood lactate reach steady state values. This conclusions was later challenged by Brickley et al. (1991), who found that in trained males, heart rate, VO_{2}, and blood lactate levels did not attain steady state during cycle ergometry exercise at CP. Brickley also concluded that there is significant inter-individual variability with respect to the amount of time exercise at CP can be performed. Hill et al. (1999) examined the relationship between critical velocity (CV) and the highest sub-maximal running velocity that can be sustained without eliciting VO_{2 max} (CV'). The results indicated a strong relationship between CV and CV' and no significant difference between them. Hill et al. (1999) concluded that CV represents the threshold velocity above which VO_{2 max} can be elicited during exercise of sufficient duration.

The AWC was originally defined as “...the total amount of work that could be performed above CP using stored energy sources within the active muscles and
independent of oxygen supply” (Monod & Scherrer 1965). Nebelsick-Gullett et al. (1988) validated the AWC from the CP model as an indirect measure of anaerobic capabilities in comparison to the Wingate test. A significant relationship was observed between AC from the Wingate test and AWC derived from the CP test. The authors concluded that the AWC determined from the CP test is a valid measure of anaerobic capabilities.

Jenkins and Quigley (1991) also assessed the validity of the AWC, but in relation to five one minute cycle ergometry work bouts. Strong significant relationships were observed between the AWC and $W_{\text{lim}}$ during the maximal interval exercise test, post-exercise venous blood pH and $(T_{\text{lim}})$, and between post-exercise venous blood pH and AWC. In addition, a weak, but significant relationship was observed between CP and AWC. The authors concluded that: 1) The AWC derived from the CP model is a valid indicator of the ability to perform intermittent, high intensity work and 2) The results confirmed the relationship between post-exercise venous blood pH, maximal interval exercise, and AWC. Dekerle et al. (2006) compared the AWC to two parameters from an all-out 90 second test ($W_{90s'}$ and $AWC_{90s}$). The authors reported no significant difference between the AWC from the CP model and $W_{90s'}$ from the all-out test. In addition, low levels of agreement were observed between the three measures. The authors concluded these data supported the claim that the AWC is a constant value and that measurements of anaerobic capability for an all-out 90-s test should not be used interchangeably to assess the AWC.
4. Application of the Critical Power Model

I. Performance Prediction

**Housh, Dona J., Terry J. Housh, and Sonja M. Bauge. "The Accuracy of the Critical Power Test for Predicting Time to Exhaustion during Cycle Ergometry."**


The purpose of this study was to determine the relationship between time to exhaustion ($T_{lim}$) during cycle ergometry exercise and predicted time to exhaustion ($P_{lim}$) derived from the critical power (CP) test. Fourteen males (22.36 ± 2.13 yr.) performed nine exhaustive cycle ergometry work bouts. The CP assessment consisted of four constant-load work bouts set at power outputs between 172-360 W. The five remaining work bouts were performed at power outputs corresponding to CP - 20%, CP, CP+ 20%, CP + 40%, and CP+ 60%. $T_{lim}$ was recorded for each of the five bouts and was compared to estimates derived from the CP model. Significant mean relationships ($r = 0.84-0.89, p < 0.05$) and no differences were observed between $T_{lim}$ and $P_{lim}$ at power outputs above CP ($p < 0.05$). At CP, the mean $T_{lim}$ was observed to be 33.31 ± 15.37 minutes. The authors concluded that: 1) the CP model produced valid estimates of time to exhaustion at power outputs above CP; and 2) the CP model tend to over-estimate the power output that can be maintained for 60 minutes by much as 17%.


The purpose of this study was to access the ability of the critical velocity (CV) test to determine time to exhaustion ($T_{lim}$) during treadmill running. Ten males (23 ± 2 yr.) performed ten exhaustive treadmill runs consisting of an incremental test, a four run CV
The purpose of this study was to assess the ability of the critical velocity (CV) test to predict marathon running performance. Six males and six females (29± 4 yr.), who were training for a marathon, performed five exhaustive treadmill running test consisting of an incremental test and four constant-velocity work bouts. The incremental test was conducted to determine \( \dot{V}O_2 \) peak and the gas exchange threshold (GET). The constant velocity test were used to determine CV preformed at running speeds between 3.6- 6.0 m·s\(^{-1}\). At least 20 minutes of rest was given between each bout. The data from the test were compared with marathon time (MT) for each subject. A significant relationship was
reported between MT and CV ($r^2 = 0.76$, p< 0.05). MT was more strongly correlated to CV than either $\dot{V}O_2$ peak or GET. CV was found to be significantly higher than marathon velocity (p<0.05). The prediction equation derived to estimate MT was: $MT = 443.5 - 78.9 \times (CV) + 34.3 \times (GET)$. The authors concluded that CV may be useful in determining marathon running performance.


The purposes of this study were to: 1) determine the accuracy of maximum velocity ($V_{max}$) estimate of the 3-parameter critical velocity model; and 2) compare the predictions of the two- and three-parameter models with respect to an 800-meter run. Seventeen males (23± 3 yr.), all trained runners, performed six exhaustive treadmill runs consisting of an incremental test and a five run CV test. The incremental test was conducted to determine $\dot{V}O_2$ max and the peak treadmill velocity (PTV). The CV test consisted of five constant-velocity runs at velocities corresponding to 95, 100, 105, 110, and 120% of PTV. In addition, both a maximal running velocity test and an 800-m time trial were performed on an indoor track to determine $V_{max}$ and 800 m time, respectfully. The $V_{max}$ estimates from both the exponential and nonlinear 3-parameter models were significantly lower than $V_{max}$ obtained from the maximal running velocity test. Significant relationships were observed between predictions from all five CV models and actual 800 m time. The two-parameter models significantly overestimates real performance. The authors concluded that the three-parameter models: 1) yield more
accurate predictions for short duration events; and 2) an accurate estimate of \( V_{\text{max}} \) is not required for its ability to predict performance.

II. Training Programs Utilizing the Critical Power


The purpose of this study was to examine the effects of six weeks of resistance training on the critical power (CP) function, time to exhaustion (\( T_{\text{lim}} \)) at CP, and \( \dot{V}O_2 \) peak. Sixteen active males (1724 yr.) performed five exhaustive cycle ergometry work bouts and a 1-RM leg press both before and after a six-week training intervention. The five work bouts consisting of an incremental exercise test to access \( \dot{V}O_2 \) peak, a 3 work bout CP test, and a work bout at CP to determine time to exhaustion (\( T_{\text{lim}} \)). The six-week resistance training intervention consisted of four exercises: Incline leg press, squats, horizontal leg press, and calf raises. Repetitions and percentage of 1-RM gradually decreased and increased, respectively. A 26.8% increase in 1-RM leg press strength was observed in the training group post-training. A significant increase was observed post-training in the AWC of the training group (\( p< 0.05 \)). The increase in AWC was negatively correlated with the change in CP (\( r= 0.94, p< 0.01 \)). No changes in \( T_{\text{lim}} \) at CP were observed. The authors concluded that the AWC is sensitive to changes from short term resistance training while CP is not significantly altered.

The purpose of this study was to assess the effectiveness of the supplementation of different interval runs intensities on the ability to elicit $\dot{V}O_2$ max for an extended duration, during a run at critical velocity (CV). Seven endurance trained males ($51\pm 4$ yr.) participated in this study. The CV for each subject was determined using their best performance from 3, 5, and 10 km races from the previous season. Four all-out running test were performed consisting of an incremental exercise test and three interval-training bouts. The incremental test was performed to determine $\dot{V}O_2$ max, its associated running velocity ($V_{max}$), and running velocity associated with lactate threshold ($V_{LT}$). The interval training consisted of three different versions of 15 second runs with intensities set between 70-110% of $V_{max}$. The three interval-training runs were set at alternating intensities of: A) 90-80% of $V_{max}$, B) 100-70% of $V_{max}$, and 3) 110-60% of $V_{max}$ and defined with the amplitudes values of low, medium, and high respectively. CV was observed to be at a high percentage of $V_{max}$ ($85.7\pm 1.4$ %). Each of the interval runs elicited $\dot{V}O_2$ max in all subjects. The high amplitude interval-training was found to result in time to exhaustion at $\dot{V}O_2$ max in half the time of the low and medium amplitude interval-training. The authors concluded that the lowest and intermediate amplitude interval-training were the most effective at eliciting $\dot{V}O_2$ max for the longest time.

The purpose of this study was to examine the effects of four weeks creatine (Cr) supplementation and high-intensity interval training (HIIT) on critical power (CP) and anaerobic work capacity (AWC). Forty-two recreationally active males (23.6± 4.8 yr.) performed a total of seven exhaustive cycle ergometry work bouts consisting of a graded exercise test (GXT) and two CP tests. The GXT was preformed to determine $\dot{V}O_2$ peak and the associated peak-power output (PP). Each CP test consisted of three work bouts with the first bout performed at 110% of PP and the remaining two were designed to elicit fatigue within 1-10 minutes. HIIT training was performed 5 days a week for six week and consisted of progressively increasing workloads with intensities based on PP. Cr supplementation was randomly assigned in a double-blind fashion where one group consumed 5g of Cr before and after training and the other group received a placebo. A significant increase in CP was observed in the Cr group post-training ($p< 0.05$). No significant differences in CP or AWC were observed in the placebo or control groups pre and post-training. The authors concluded that supplementation of Cr along with HIIT can be effective in improving CP.

**Summary**

This section focused on the ability of the critical power (CP) model to predict performance and its sensitivity to different modes of exercise training. Housh et al.
(1989) assessed the ability of the critical power (CP) model to predict time to exhaustion ($T_{lim}$). The actual $T_{lim}$ values to 5 constant power output rides above CP were compared with the predicted time to exhaustion derived using the CP model ($PT_{lim}$) with the equation $T_{lim} = \frac{AWC}{[P-CP]}$. The results indicated a strong significant relationship and no significant differences between $T_{lim}$ and $PT_{lim}$. The authors concluded that 1) the CP model produced valid estimates of time to exhaustion at power outputs above CP; and 2) the CP model tended to over-estimate the power output that can be maintained for 60 minutes by 17%. Pepper et al. (1992) also observed an over-estimation in predicted running velocities that could be maintained for 60 minutes when they applied the critical velocity (CV) model to treadmill running. Pepper et al. (1992) concluded that their study did not support the validity of the CV model to predict $T_{lim}$ during treadmill running.

Florence and Weir (1997) assessed the CV models ability to predict marathon running times (MT). The results reported a strong significant relationship between MT and CV and that MT was more strongly correlated with CV than either $\dot{V}O_2 \text{peak}$ or the gas exchange threshold. Bosquet at al. (2006) assessed the validity and significance of the maximum velocity ($V_{max}$) from the CV model to predicting 800 meter times. The results indicated the CV model tended to under-estimate $V_{max}$ and the two-parameter models tended to overestimate actual performance. Significant relationships were reported between all two- and three-parameter CV model prediction times and actual 800 meter times. The authors concluded that the three-parameter model: 1) yielded more accurate predictions for short duration events; and 2) an accurate estimate of $V_{max}$ is not required for its ability to predict performance.
A few studies have also been developed to assess the effects of various modes of training on the CP model. Bishop et al. (1996) examined the effects of short-term resistance training on the parameters of CP and \( T_{\text{lim}} \) at CP. The results indicated a significant increase in the AWC post-training and no changes in either CP or \( T_{\text{lim}} \) at CP. The authors concluded that the AWC is sensitive to changes from short term resistance training. Kendall et al. (2009) examined the effects of short-term high-intensity interval training and creatine supplementation on both the CP and AWC. The results indicated a significant increase in the CP post-training with supplementation of CP, along with no significant changes in the AWC. The authors concluded that supplementation with Cr in conjunction with HIIT can be effective in improving CP. Billat et al. (2001) examined the effects three different amplitudes of short duration interval runs on the ability to maintain \( \dot{V}O_2 \) for greater than 10 minutes. The high amplitude interval-training was found to result in time to exhaustion at \( \dot{V}O_2 \) max in half the time of the low and medium amplitude interval-training. The authors concluded that the lowest and intermediate amplitude interval-training were the most effective at eliciting \( VO_2 \) max for the longest time.

5. Protocol Variations

I. Mathematical Modeling


The purposes of this study were to: 1) compare the estimates of critical power (CP) and goodness of fit of 5 CP models; and 2) determine the relationship between each CP estimate and the ventilatory threshold (\( V_T \)). Sixteen males (21.1± 1.3 yr) performed
six to eight exhaustive cycle ergometry work bouts, consisting of an incremental exercise test (IXT) and multiple constant-load tests. The IXT was performed to determine the power output range for the CP assessment. The CP assessment consisted of five to seven constant-load work bouts. The selected power outputs were determined from the peak power achieved during the incremental test and time to exhaustion (T_{lim}) was recorded for each test. Six subjects underwent additional testing, which consisted of the monitoring of gas exchange parameters during the IXT and several constant-load work bouts. The work bouts, each 40 min in duration or until exhaustion, were to determine the highest power output that could be maintained for 40 minutes, without a rise in ventilation between minute 20 and minute 40 of exercise. 

This power output was defined as V_{T}. The five critical power models examined for this study were the: 1) Three-parameter nonlinear; 2) Two-parameter nonlinear; 3) Linear power; 4) Linear total work; and 5) Exponential model. Significant differences were observed between the five different models. The three-parameter nonlinear model resulted in the lowest estimates for CP and the highest estimates for anaerobic work capacity (AWC) while the linear power model resulted in the highest estimate of CP and the lowest estimate of AWC. The coefficient of determination for the linear power model was significantly lower than each of the other models ($r^2 = 0.96 \pm 0.03$, P< 0.05), which were not significantly different from each other. The V_{T} was not significantly different from the CP estimate derived from the three-parameter model (P< 0.05). A significant relationship was reported between the V_{T} and CP estimates from all five models ($r= 0.69-0.91$, P< 0.05). The authors concluded that: 1) considerable differences can result in the estimates for CV derived from the five models examined in this study; and 2) the three-
The parameter nonlinear is preferred because it does not assume infinite power and it does not differ greatly from the $V_T$.


The purpose of this study was to examine the effect of mathematical modeling on critical velocity (CV) estimates and their corresponding $\dot{V}O_2$, heart rate, and blood lactate values. Ten males (22 ± 2 yrs.) performed five exhaustive treadmill work bouts in the form of an incremental exercise test and four constant velocity tests. The incremental exercise test was used to determine $\dot{V}O_2$ max. The $\dot{V}O_2$, heart rate, and blood lactate were monitored for each constant-velocity test. The constant velocity tests were utilized to assess CV and consisted of four randomly ordered exhaustive treadmill runs at velocities ranging from 14.5 to 19.3 km/h. Time to exhaustion was recorded for each test.

Five different CV models were utilized to determine CV for each subject. The different CV models utilized and their respective equations included: the Linear Total Distance model ($TD = AWC + CV \cdot t$), the Linear-velocity model ($v = \frac{AWC}{t} + CV$), The Nonlinear-2 model ($t = \frac{AWC}{v-CV}$), the Nonlinear-3 model ($t = \left[\frac{AWC}{v-CV}\right] - \left[\frac{AWC}{V_{max}-CV}\right]$), and the exponential model ($v = CV + (V_{max} - CV)^{\frac{1}{T}}$). Values for $\dot{V}O_2$, heart rate, and blood lactate corresponding to the CV estimates were determined from linear regression from the relationships between HR, $\dot{V}O_2$, and velocity from the incremental velocity test.

Significant differences were reported for the mean values for CV, $\dot{V}O_2$, heart rate, and blood lactate among the 5 models. The lowest and highest mean estimates for CV were from the nonlinear-3 and the exponential models, respectively, with an observed
difference of 19.5% between them. The authors concluded that: 1) considerable
differences can result in the estimates for CV derived from the five models examined in
this study; and 2) the nonlinear-3 model produced the most conservative estimates of CP
of the models examined along with the percent of maximal values for $\dot{V}O_2$, heart rate,
and blood lactate of 89%, 93%, and 63%, respectively.

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The purposes of this study were to: 1) re-examine the findings of Gaesser et al.
(1995), by comparing the critical power (CP) estimates derived from 5 CP models; and 2)
to determine the time to exhaustion ($T_{\text{lim}}$) during cycle ergometry at the lowest estimate
of CP from the 5 models. Nine males (25± 3 yr) performed eight or nine exhaustive cycle
ergometry work bouts, consisting of an incremental exercise test, multiple constant-load
tests, and two tests at CP. The incremental exercise test was performed to determine peak
power output (PP). The PP was used to determine the power output range for the CP
assessment. The CP assessment consisted of five or six constant-load work bouts and
time to exhaustion ($T_{\text{lim}}$) was recorded for each test. The five critical power models
originally implemented by Gaesser et al. (1995) were used for the determination of CP in
this study. The mathematical model that resulted in the lowest CP estimate was then used
to perform two trials at its respective CP. The trials were performed for a duration of 60
min or until exhaustion and rate of perceived exertion and heart rate were recorded
monitored throughout the test. The three-parameter nonlinear model resulted in the lowest
mean estimates for CP and the lowest estimates for each subject. During the trial at CP,
two of the nine subjects were unable to complete 60 min of cycling during either trial.
The \( T_{\text{lim}} \) for these subjects during the first and second trials ranged from 18- 48.1 minutes. The authors concluded that: 1) the three-parameter nonlinear model produced the lowest mean estimates for CP of the five models examined; and 2) these five CP models tended to overestimate the power output that can be maintained for a minimum of 60 min, using cycle ergometry.


The purpose of this study was to examine the CP and AWC estimates from the five critical power (CP) models described by Gaesser et al. (1995) along with estimates derived from the three minute all-out test described by Burnley et al. (2006). Five females and four males (23± 3 yr.) performed six exhaustive cycle ergometry work bouts consisting of an incremental exercise test (IET), 4 constant-load tests, and a three-minute all-out test (CP\(_{3\text{min}}\)). The IET was used to determine the power output associated with \( \dot{\text{VO}}_2 \) peak (peak power) and the gas exchange threshold (GET) which was defined as the breakpoint in the \( \text{VCO}_2 \) versus \( \dot{\text{VO}}_2 \) relationship. The 4 constant-load tests were used to determine CP and AWC from the five mathematical models. Intensities of two of the work bouts were set by adding the GET and two respective percentages of the difference between GET and \( \dot{\text{VO}}_2 \) peak (\( \Delta \)) at GET+70\%\( \Delta \) and GET+ 80\%\( \Delta \). The remaining two work bout intensities were set at 100\% and 105\% of \( \dot{\text{VO}}_2 \) peak. The five critical power models originally implemented by Gaesser et al. (1995) were used for the determination.
of five estimates of CP and four estimates of AWC in this study. For the three-minute all-out test, the resistance was set using the linear mode of the electronically-braked cycle ergometer and was equal to: \( \text{GET} + 50\% \Delta / 70^2 \). The CP and AWC were determined as the average power output over the last 30s of the test and the integral of the power vs. time relationship above CP, respectively. Significant mean differences were reported among the 6 CP estimates (P<0.001) and among the 5 AWC estimates (P< 0.001). For CP, the nonlinear three-parameter model produced the lowest estimates and both the exponential model and \( \text{CP}_{3\text{min}} \) produced the highest estimates. For AWC, the three-parameter model and two-parameter model produced significantly higher estimates than the other 3 models. The authors concluded that CP and AWC derived from the nonlinear three-parameter model accurately estimates the asymptote of the power duration curve, the demarcation of the heavy to severe exercise intensity domain, and the anaerobic capabilities.

II. Work Bouts


The purpose of this study was to determine the number of work-bouts necessary to achieve accurate estimates of critical power (CP) and anaerobic work capacity (AWC). 12 healthy males (20-27 yr.) performed four constant power output (P), cycle ergometer work-bouts ranging from 172-360 W depending on their activity level. The work-bouts intensities were set high enough to result in exhaustion within 1- 10 minutes. The time to exhaustion (\( T_{\text{lim}} \)) was recorded for each work-bout and was plotted against limit work
(W_{lim}), which was derived using the equation: W_{lim} = P (T_{lim}). The CP and AWC were defined as the slope and y-intercept of the W_{lim} versus T_{lim} relationship, respectively. Both CP and AWC were calculated using all combinations of two and three work-bouts and were compared with the values obtained from using all four work-bouts as the criterion measurement. The results demonstrated that only the values for CP (r= 0.80) and AWC (r= 0.51) derived from the combination of the second and third highest intensity work-bouts were significantly different from the criterion measurement. The combination of the highest and lowest intensity work-bouts demonstrated a significant relationship with the criterion measure for both CP (r= 0.99) and AWC (r= 0.98). Based on these data, the authors concluded that CP and AWC can be accurately estimated using only two work bouts, provided that: 1) the T_{lim} of the work-bouts range from 1-10 minutes; and 2) T_{lim} of the work bouts differ by a minimum of 5 minutes.


The purpose of this study was to determine whether the critical swimming velocity (CV) corresponds to the velocity at lactate threshold (V_{LTH}). Eight elite triathletes (26± 4 yr.) performed five maximal effort swims of 100, 200, 400, 800, and 1500 m with a minimum of 24 hours between each swim. The CV was determined using all combinations of 2- 5 swims. V_{LTH} was determined by 5 x 300 m swims of increasing velocity that were paced using an Aquapacer. Blood lactate samples were taken after each swim and the lactate threshold was determined as the point of first inflection of the lactate-work rate curve. No significant differences were observed as a result of the number of trials used in the linear regression (p< 0.05). Combinations of only the shorter distance trials resulted in
higher CV estimates than combinations of longer distances. The mean CV $(1.23 \pm 0.11 \text{ m·s}^{-1})$ was observed to be significantly different than mean $V_{LTH} (1.15 \pm 0.10 \text{ m·s}^{-1})$. Mean blood lactate levels were significantly higher at CV than at the lactate threshold $(p< 0.05)$. The authors concluded that CV cannot be used as a non-invasive method of determining the lactate threshold because it consistently results in an over-estimation of $V_{LTH}$.

III. Time to Exhaustion


The purpose of this study was to determine whether the choice of predictive tests would result in significant differences in estimates of the critical power (CP) and the anaerobic work capacity (AWC). Ten females (18.6± 1.7 yr.) performed five exhaustive cycle ergometry work bouts at power outputs individually chosen to result in $T_{lim}$ between 1-10 minutes. CP and AWC estimates were derived using both the linear total-work (LTW) and the Non-linear power-time (PT) model. Three different combinations of the 5 power outputs tested on each models respective plot were used to derive CP and AWC, including: The first, third, and fifth power output in ascending order of intensity, the three lowest power outputs, and the three highest power outputs. Significant difference were observed between the mean values for CP and AWC from the power output combinations of the LTW and PT models $(p<0.05)$. The authors concluded that for a valid estimate of CP to be attained for the CP model, the predictive tests should be selected over a wide range of power outputs.

The purpose of this study was to assess the validity of critical velocity (CV) for determining performance outcomes in elite swimmers. 17 male swimmers participated in the CV assessment, nine of which also participated in $\dot{V}O_2$ max and onset of blood lactate accumulation (OBLA) tests. The CV was determined from maximal effort swims at four different distances (50, 100, 200, and 400 meters). Time to completion was recorded for each swim. The average swimming velocity was determined using the equation: $V = \frac{D}{T}$.

Distance (D) was plotted against time to completion (T) and described by the equation: $d = a + b \cdot t$. The results demonstrated a strong linear relationship between D and T ($r^2 = 0.997$, $P < 0.001$). Significant relationships were also observed between mean velocities in the 200 m and 400 m freestyle ($r = 0.776$, $P < 0.01$), CV and mean velocity in 200 m freestyle ($r = 0.781$, $P < 0.01$), and CV and mean velocity in 400 m freestyle ($r = 0.99$, $P < 0.001$). The authors concluded that CV can be determined from performing several maximal effort swims at predetermined distances.
IV. The Three-Minute All-Out Test


The purpose of this study was to determine if the 3-min all-out cycling test would:

1) elicit a $\dot{V}O_2$ peak; and 2) provide an estimate of a valid measure of the maximal steady-state power-output. Eleven subjects (nine males, 27± 7 yr.), all recreationally trained, performed five cycle ergometry work bouts consisting of a ramp protocol test, two 3-minute all-out test, and two constant-load work bouts. The ramp test was conducted to determine $\dot{V}O_2$ peak and the gas exchange threshold (GET). For the 3-minute all-out test, the subjects started with 3 minutes of unloaded cycling at a cadence of 90 rev·min$^{-1}$. The subjects increased their cadence to approximately 120 rev·min$^{-1}$, 5 seconds before beginning the all-out effort. The resistance was set using the linear mode of the cycle ergometer at a power output equal to halfway between $\dot{V}O_2$ peak and the GET at each subject's preferred cadence between 80- 90 rev·min$^{-1}$. End-stage power (EP) and work performed above end-stage power (WEP) were calculated as the average power output for the final 30-s of the test and the power-time integral above EP, respectfully. The two constant-load work bouts were performed for 30 minutes or to exhaustion at a power output of 15 W above and below EP from the 3-minute all-out test. No significant difference was observed between $\dot{V}O_2$ achieved during the ramp test and the 3-minute all-out test ($p <0.05$). For the constant-load test conducted at 15 W below EP, 9 of 11 subjects were able to complete 30 min of exercise. None of the subjects were able to
complete a full 30 min at 15 W above EP. The authors concluded that a three-minute all-out test can be used to elicit a $\dot{V}O_2$ peak and to estimate maximal steady-state power output.


The purpose of this study was to compare the parameters of the critical power (CP) model with those derived from the 3-min all-out test, specifically CP to end-test power (EP) and anaerobic work capacity to work done above EP (WEP). Ten trained subjects (33± 9 yr.) performed seven exhaustive cycle ergometry work bouts consisting of an incremental test, a 3-minute all-out test, and five constant-load work bouts. The incremental test was conducted to determine $\dot{V}O_2$ peak and the gas exchange threshold (GET). The 3-minute all-out test used the same protocol as Burnley et al. (2006). The CP assessment consisted of five constant-load work bouts at 70 and 80% of the magnitude of the interval between GET and $\dot{V}O_2$ peak ($\Delta$), 100 and 105% of $\dot{V}O_2$ peak, and the final bout was conducted at either 60%$\Delta$ or 110% $\dot{V}O_2$ peak. Linear regression was used to derive CP and AWC using two linear CP models. No significant differences were observed between CP and EP or between AWC and WEP (p< 0.05). Significant relationship were observed between estimates of CP and EP ($r= 0.99$, p< 0.05) and between AWC and WEP ($r= 0.84$, p< 0.05). The authors concluded that the three-minute all-out test produced valid estimates of the parameters of the CP model.

The purpose of this study was to develop a 3-minute all-out test (CP_{3min}) protocol using cycle ergometry for estimating critical power (CP) and anaerobic work capacity (AWC) with resistance based on body weight. Six males and six female, (23.2± 3.5 yr.) moderately trained subjects, performed eight exhaustive cycle ergometry work bouts consisting of an incremental test, four constant-load work bouts, and three 3-minute all out tests. The incremental test was conducted to determine V̇O₂ peak and the gas exchange threshold (GET). The CP assessment consisted of five constant-load work bouts at intensities set at 70 and 80% of the magnitude of the interval between GET and V̇O₂ peak (Δ), 100 and 105% of V̇O₂ peak. The first CP_{3min} test used the same protocol as Burnley et al. (2006). The remaining two 3-minute all-out tests were performed against a resistance of 3.5% (CP_{3.5%}) and 4.5% (CP_{4.5%}) of body weight in a random order. CP and AWC for all of the 3-minute all-out tests were determined as the average power output over the last 30s of the test and the power-time integral above CP, respectfully. No significant mean differences were observed between the CP derived from the CP test, CP_{3.5%}, and CP_{4.5%}. Mean CP derived from the CP_{3min} was significantly greater than values derived from the CP test and CP_{3.5%} (p< 0.05). The were no significant mean differences for AWC between the CP test, CP_{3min}, and CP_{4.5%}. Values obtained for the estimates of AWC from the CP test and CP_{3min}, were significantly greater than CP_{3.5%}. The authors concluded that a single work...
bout test with, resistance set at 4.5% of the individuals body weight, provides a practical and accessible way to estimate CP and AWC.

**Summary**

This section focused on protocol variations of the critical power (CP) test and how they can affect the validity of the estimates of its parameters. The factors examined included mathematical modeling, number of work bouts, time to exhaustion ($T_{lim}$) of the work bouts, and the three minute all-out test. Gaesser et al. (1995) examined the effects of mathematical modeling on CP estimates. The five critical power models examined for this study were the: 1) three-parameter nonlinear; 2) two-parameter nonlinear; 3) linear power; 4) linear total work; and 5) exponential model. Significant differences were observed among the five different models. The three-parameter nonlinear model resulted in the lowest estimates for CP and the highest estimates for anaerobic work capacity (AWC). The authors concluded that considerable differences can result in the estimates for CP derived from these five models and the three-parameter nonlinear model is preferred. Housh et al. (2001) came to the same conclusion as Gaesser et al. (1995) when they applied the same five CP models to treadmill running to examine the effect of mathematical modeling on the estimation of the critical velocity (CV). Bull et al. (2000) reexamined the finding of Gaesser et al. (1995) and also examined time to exhaustion ($T_{lim}$) at the lowest estimate for CP, which was derived from the three-parameter nonlinear model. Of the nine subjects, two were unable to complete a 60 min work bout at CP. The authors concluded that these five CP models tend to overestimate the power output that can be maintained for a minimum of 60 min.
Bergstrom et al. (2012) examined estimates of the CP and the anaerobic work capacity (AWC) from the 5 CP models originally described by Gaesser et al. (1995) along with estimates derived from the three minute all-out test described by Burnley et al. (2006). The results for CP indicated that the nonlinear three-parameter model produced the lowest estimates and both the exponential model and CP$_{3\text{min}}$ produced the highest estimates. For AWC, the three-parameter and two parameter models produced significantly higher estimates than the other 3 models. The authors concluded that CP and AWC derived from the nonlinear three-parameter model accurately estimates the asymptote of the power duration curve, the demarcation of the heavy to severe exercise intensity domain, and the anaerobic capabilities.

The number of work bouts that are necessary to accurately estimate the CP and AWC was investigated by Housh et al. (1990). Various combinations of two, three, or four exhaustive work bouts were examined against the criterion measurement derived from using all four work bouts. The results indicated that the combination of the highest and lowest intensity work-bouts demonstrated a significant relationship with the criterion measure for both CP and AWC. The authors concluded that CP and AWC could be accurately estimated using only two work-bouts, provided that: 1) the $T_{\text{lim}}$ of the work-bouts range from 1-10 minutes; and 2) $T_{\text{lim}}$ of the work-bouts differ by a minimum of 5 minutes. Martin and Whyte (2000) examined whether the CV for swimming corresponded to the swimming velocity at lactate threshold (V$_{\text{LTH}}$). Five maximal effort swims of 100, 200, 400, 800, and 1500 m were performed and all combinations of 2-5 swims were analyzed. No significant differences were observed as a result of the number of trials used in the linear regression and combinations of only the shorter distance trials resulted in higher CV estimates than combinations of longer distances.
Bishop et al. (1998) examined whether the choice of predictive tests would result in significant differences in estimates of the CP and AWC. Five exhaustive work bouts were performed at power outputs individually chosen to result in $T_{lim}$ between 1-10 minutes. Three different combinations of the 5 power outputs on each model's respective plot were used to derive CP and AWC. Significant differences were observed between the mean values for CP and AWC from the power output combinations. The authors concluded that for a valid estimate of CP to be attained for the CP model, the predictive tests should be selected over a wide range of power outputs. Wakayoshi et al. (1993) assess the validity of CV for determining performance outcomes. Maximal effort swims at four different distances (50, 100, 200, and 400 meters) were performed. Significant relationships were observed between mean velocities in the 200 m and 400 m freestyle, CV and mean velocity in 200 m freestyle, and CV and mean velocity in 400 m freestyle. The authors concluded that CV can be determined from performing several maximal effort swims at predetermined distances. The three-minute all-out test ($CP_{3min}$) was originally hypothesized by Burnley et al. (2006) as a method of measuring VO$_2$ peak and maximal steady-state power output. The resistance for the $CP_{3min}$ required an assessment of the VO$_2$ peak and the GET for each subject. No significant difference was observed between the VO$_2$ peak value elicited from a ramp protocol test and the $CP_{3min}$. For the constant-load test conducted at 15 W below EP, 9 of 11 subjects were able to complete 30 min of exercise while, none of the subjects were able to complete a full 30 min at 15 W above EP. The authors concluded that the $CP_{3min}$ can be used to elicit a VO$_2$ peak and to estimate maximal steady-state power output. Vanhatalo et al. (2007) then compared the end-test power (EP) and the work done above EP (WEP) from the 3-min all-out test, to
the critical power (CP) and the anaerobic work capacity (AWC) from the CP models, respectfully. The results indicated no significant differences and strong significant relationships between CP and EP and between AWC and WEP, respectfully. The authors concluded that the three-minute all-out test produced valid estimates of the parameters of the CP model. Bergstrom et al. (2012) proposed a new 3-minute all-out test using resistance based on body weight instead of gas exchange parameters. The Results indicated no significant mean differences between CP and AWC estimates from the CP model and the 3-minute all-out tests performed against a resistance of and 4.5% (CP4.5%) of body weight. The authors concluded that a single work bout test with resistance based on the individuals’ body weight provides an accurate estimate of the CP and AWC without the need to use gas exchange parameters.
Chapter III: Methods

Experimental Design

The subjects in this study completed 1 or 2 visits. During the first visit, the subjects completed the written survey of swimming performance. The survey requested the subjects to provide their fastest long-course swimming performance times ($AT_{com}$) at standard distances (100, 200, 400, 800, 1200 and 1500 meters) that are generally swum in competitions, and to estimate completion times ($IT_{com}$) on non-standard long-course distances (150, 300, 500, and 1100 meters). Two separate regression analyses were performed to determine the parameters of the critical velocity (CV) test using the standard distances versus $AT_{com}$ and the non-standard distance versus $IT_{com}$ relationships. The CV test parameters determined from the non-standard distance versus $IT_{com}$ relationship were then used to predict times to completion for the standard distances. The second visit was optional for subjects and consisted of them visiting the laboratory to complete a Bioelectrical Impedence Analysis (BIA) for body composition assessments.

Subjects

Thirty-two (16 males, 16 females) collegiate swimmers with a mean age of 20.1 ± 1.0 yrs were recruited for this study. Subjects were all members of the University of Kentucky swim team and were recruited via word of mouth. All of the subjects whose respective stroke specialties did not include the front crawl stroke were excluded, along with subjects whose estimations resulted in non-physiologic parameters of the CV model. These exclusions resulted in the reduction of the number of subjects to fourteen (8 males, 6 females). Prior to testing, each subject completed a written informed consent document.
and all testing procedures were approved by the University’s Intuitional Review Board for Human Subjects.

**BIA Analysis**

Body composition assessments were completed with a Bioelectrical Impedence Analysis (BIA; Bodystat QuadScan 4000) on twelve of the subjects. Subjects who were interested in receiving a Bioelectrical Impedence Analysis (BIA) reported to the University of Kentucky’s Exercise Physiology laboratory at an agreed upon time. After the necessary demographic information was recorded, the subjects were given a brief explanation of the procedure. The BIA device was calibrated before measurements were taken and subjects were instructed to lay in a supine position on a non-conductive surface. For each subject, the impedance at all frequencies provided (5, 50, 100 & 200 kHz), percent body fat, and total body water were recorded.

**Inquiry of Performance**

Each subject completed a written survey (Appendix A) requesting them to provide demographic information, the fastest long-course swimming performance times at standard distances (100, 200, 400, 800, 1200 and 1500 meters), and to estimate completion times on non-standard long-course distances (150, 300, 500, and 1100 meters). Each actual performance time to completion (AT$_{com}$) and inquired time to completion (IT$_{com}$) was made to the nearest second. The assumptions for the performance inquiries were: 1) the front crawl swimming stroke was used; 2) each swim started off the block; and 3) the pool was 50 meters in length.

**Data Analyses**

Each standard total distance (TD) was plotted against its corresponding AT$_{com}$. A total of three to four distances were used to derive the regression line, depending on the
number of performance times provided by each subject (19,29). The \( \text{CV}_{\text{ACT}} \) and \( \text{ADC}_{\text{ACT}} \) were determined from the TD versus AT\(_{\text{com}}\) relationship. The \( \text{CV}_{\text{ACT}} \) and \( \text{ADC}_{\text{ACT}} \) were defined as the slope and y-intercept, respectively, of the regression line (TD= \( \text{ADC}_{\text{ACT}} + \text{CV}_{\text{ACT}} \cdot \text{AT}_{\text{com}} \)).

Each non-standard TD was plotted against its corresponding IT\(_{\text{com}}\). Different combinations of three to four distances were used to form each regression line. The \( \text{CV}_{\text{inq}} \) and \( \text{ADC}_{\text{inq}} \) were determined from the TD versus IT\(_{\text{com}}\) relationship. The \( \text{CV}_{\text{inq}} \) and \( \text{ADC}_{\text{inq}} \) were defined as the slope and y-intercept, respectively, of the regression line (TD= \( \text{ADC}_{\text{inq}} + \text{CV}_{\text{inq}} \cdot \text{IT}_{\text{com}} \)).

Estimates of actual performance times were derived using the \( \text{CV}_{\text{inq}} \) and \( \text{ADC}_{\text{inq}} \) parameters from the TD versus IT\(_{\text{com}}\) relationship, along with the average swimming velocities (V) calculated for each standard distance from the AT\(_{\text{com}}\) \( (V=\frac{\text{TD}}{\text{AT}_{\text{com}}}) \). These inquiry-estimated times to completion (IET\(_{\text{com}}\)) were derived for each of the standard distances using the equation: IET\(_{\text{com}}\)= \( \frac{\text{ADC}_{\text{inq}}}{(V-\text{CV}_{\text{inq}})} \)

**Statistical Analysis**

Four subjects were excluded from the analysis because the regression line derived from their respective TD versus IT\(_{\text{com}}\) relationships resulted in non-physiologic \( \text{ADC}_{\text{inq}} \) estimates (\( \text{ADC}_{\text{inq}} < 10 \) meters). Previous studies have reported ADC estimations in well-trained adult swimmers to generally be greater than 10 meters (13, 41). For the remaining subjects (\( n=14 \)), only distances between 100- 800 meters were analyzed due to: 1) a limited number of subjects providing performance times for longer distances; and 2) the exclusion of data for any distance where a subject’s \( \text{CV}_{\text{inq}} \) was greater than their actual velocity for that specific distance.
The mean differences between: 1) \(CV_{ACT}\) and \(CV_{inq}\); 2) \(ADC_{ACT}\) and \(ADC_{inq}\); and 3) \(IET_{com}\) and \(AT_{com}\) at each distance (100-800 meters), were analyzed using separate paired samples t-tests. Linear regression analyses were used to determine the Pearson product-moment correlations, coefficients of determination and the standard error of the estimates (SEE) between: 1) \(IET_{com}\) and \(AT_{com}\) at each distance (100-800 meters); 2) \(CV_{ACT}\) and \(CV_{inq}\); and 3) \(ADC_{ACT}\) and \(ADC_{inq}\). Modified Bland-Altman plots with the difference (\(ACT - inq\)) plotted against the criterion measurement (\(CV_{ACT}, ADC_{ACT}, \) or \(AT_{com}\)) were used to assess the agreement between: 1) \(AT_{com}\) and \(IET_{com}\) at each distance (100-800 meters); 2) \(CV_{ACT}\) and \(CV_{inq}\); and 3) \(ADC_{ACT}\) and \(ADC_{inq}\). Agreement was analyzed specifically using: 1) the mean difference for each measurement; 2) The limits of agreement set at ± 1.96 SD; and 3) the correlation between actual values and the difference. In addition, regression analyses were used to determine the strength of the relationship between the total distances and times to completion (\(IT_{com}\) and \(AT_{com}\)) for each subject. For these analyses, each of the distances (100, 150, 200, 350, 400, 800 m) were plotted against their respective \(IT_{com}\) or \(AT_{com}\) values for each subject. The distances and times to completion served as the independent and dependent variables, respectively.
Chapter IV: Analysis of Data

Results

The descriptive characteristics of the subjects (n = 14) are presented in Table 1. Each subject’s actual and inquired parameters of the critical velocity model are presented in Table 2. There was no mean difference (t(13) = 1.01, p = 0.32) between \( CV_{ACT} \) (mean \( \pm \) SD 1.480 \( \pm \) 0.055 m \( \cdot \) s\(^{-1} \)) and \( CV_{inq} \) (1.495 \( \pm \) 0.068 m \( \cdot \) s\(^{-1} \)) and they were significantly related (r = 0.61, p < 0.021) (Figure 1). In addition, there was no mean difference (t(13) = -0.13, p = 0.90) between \( ADC_{ACT} \) (25.11 \( \pm \) 8.68 m) and \( ADC_{inq} \) (24.87 \( \pm \) 9.37 m) and they were significantly related (r = 0.72, p < 0.004) (Figure 2). The coefficients of determination (\( r^2 \)) for the total distance (TD) versus \( AT_{com} \) ranged from 0.9975 to 0.9999 (0.9995 \( \pm \) 0.0007) and the SEE ranged from 2.452 s to 18.875 s (7.122 \( \pm \) 4.776 s). The \( r^2 \) values for the TD versus \( IT_{com} \) ranged from 0.9948 to 0.9999 (0.9993 \( \pm \) 0.0013), respectively, and the SEE ranged from 1.38 s to 36.05 s (10.43 \( \pm \) 8.60 s), respectively.

For the comparison of the \( AT_{com} \) and \( IET_{com} \), the results of the paired samples t-tests indicated the \( AT_{com} \) (55.99 \( \pm \) 3.47 s) was significantly (t(13) = 4.69, p < 0.001) faster than the \( IET_{com} \) (82.44 \( \pm \) 20.15 s) for the 100 meter swim. There were, however, no mean differences between \( AT_{com} \) and \( IET_{com} \) at 200 m (\( AT_{com} = 118.21 \pm 5.33 \) s and \( IET_{com} = 121.52 \pm 28.20 \) s), 400 m (\( AT_{com} = 249.38 \pm 9.92 \) s and \( IET_{com} = 247.84 \pm 54.27 \) s), or 800 m (\( AT_{com} = 520.11 \pm 16.31 \) s and \( IET_{com} = 751.14 \pm 501.19 \) s). Furthermore, there were no significant relationships between the \( AT_{com} \) and \( IET_{com} \) (r = 0.039 to 0.312, p > 0.05) for any of the distances (Figures 3 to 6).

The results of the Bland-Altman analyses are presented in Figures 7 to 12. The 95% LOA for the \( CP_{ACT} \) and \( CP_{inq} \) estimates ranged from -0.13 to 0.09. There was no
significant relationship between the mean difference (CP_{ACT} – CP_{inq}) and the criterion, CP_{ACT} (Figure 7). The 95% LOA for the ADC_{ACT} and ADC_{inq} estimates ranged from -13.10 to 13.58. There was no significant relationship between the mean difference (CP_{ACT} – CP_{inq}) and the criterion, CP_{ACT} (Figure 8). The 95% LOA for the AT_{com} and IET_{com} at 100 m ranged from -66.29 to 13.37. There was no significant relationship between the mean difference (AT_{com} – IET_{com} ) and the criterion, AT_{com} (Figure 9). The 95% LOA for the AT_{com} and IET_{com} at 200 m ranged from -62.69 to 56.05. There was no significant relationship between the mean difference (AT_{com} – IET_{com} ) and the criterion, AT_{com} (Figure 10). The 95% LOA for the AT_{com} and IET_{com} at 400 m ranged from -108.40 to 111.47. There was no significant relationship between the mean difference (AT_{com} – IET_{com} ) and the criterion, AT_{com} (Figure 11). The 95% LOA for the AT_{com} and IET_{com} at 800 m ranged from -1208.55 to 746.48. There was no significant relationship between the mean difference (AT_{com} – IET_{com} ) and the criterion, AT_{com} (Figure 12).

There were significant relationships for the distance (100, 150, 200, 350, 400, 500, 800, 1100 m) versus time (both AT_{com} and IET_{com}) for each subject. The regression coefficients (r) ranged from 0.995- 0.999 (p < 0.001), the r^2 from 0.990- 0.999, and the standard error from 1.646- 36.155 seconds (Figures 13 to 26).

Discussion

The primary objective of this study was to determine if collegiate swimmers could accurately estimate the parameters of the CV model via performance estimations at non-standard swimming distances. This was the first study to collect data from a combination of both male and female collegiate swimmers for the determination of the CV parameters. Three or four standard collegiate race distances (i.e., total distance; TD) for the front
crawl (100, 200, 400 and 800 m) were plotted as a function of the AT\text{com} (i.e., the reported performance times for each distance). In addition, four non-standard race distances (150, 350, 500, 1100 m) were plotted against the IT\text{com}. The TD versus AT\text{com} and TD versus IT\text{com} relationships were described by the equations: TD = ADC_{ACT} + CV_{ACT} (AT\text{com}) and TD = ADC_{inq} + CV_{inq} (IT\text{com}), respectively. The r\textsuperscript{2} values for both the TD versus AT\text{com} and the TD versus IT\text{com} relationships were consistent with the r\textsuperscript{2} values (0.997- 1.000) reported from previous studies of collegiate-aged, trained swimmers (39, 41), and indicated a very high goodness of fit of the model. In addition, the SE values of the parameters for CV\text{ACT} and ADC\text{ACT} (SE = 0.019 m\cdot s\textsuperscript{-1} and 7.121 m, respectively) were similar to the SE values for the CV\text{inq} and ADC\text{inq} (SE = 0.022 m\cdot s\textsuperscript{-1} and 8.943 m, respectively). Thus, the highly linear relationship between TD and IT\text{com} indicated that the mathematical model used to derive CV\text{ACT} and ADC\text{ACT} from actual performance times was also applicable for inquired swimming performance times.

The estimates of the CV\text{ACT}, CV\text{inq}, ADC\text{ACT}, and ADC\text{inq} were consistent with values reported from previous studies of collegiate male swimmers (39, 40, 41). Specifically, the CV and ADC values reported by Wakayoshi (39) (1.437 ± 0.024 m\cdot s\textsuperscript{-1} and 23.30 ± 1.72 m, respectively) were very similar to both: 1) the mean actual CV and ADC values (1.480 ± 0.055 m\cdot s\textsuperscript{-1} and 25.11 ± 8.68 m, respectively) in the present study; and 2) the mean inquired CV and ADC values (1.495 ± 0.068 m\cdot s\textsuperscript{-1} and 24.874 ± 9.365 m, respectively) in the present study. The Bland-Altman plots (Figures 7-8) revealed no systematic bias between actual and inquired measures for either parameter (CV = -0.016 ± 0.056 m\cdot s\textsuperscript{-1}, p = 0.407; ADC = 0.239 ± 6.807 m, p = 0.320). In addition, there were moderate relationships between CV\text{ACT} and CV\text{inq} (r = 0.61, p< .05) as well as ADC\text{ACT}
and ADC_{inq} (r = 0.72, p< .05). The SEE values for the comparison between CV_{ACT} and CV_{inq} (SEE = 0.047 m·s^{-1}) and between ADC_{ACT} and ADC_{inq} (SEE = 6.53 m) fell within 5% and 30% of the actual mean values, respectively. The error for the CV comparison was within the error typically reported (~10 - 20%) for indirect physiological measures, however the error for the ADC comparison was not (14, 28). In contrast to cycle ergometry and running, which rely mainly on the lower extremities for force production, propulsion in swimming requires total body work that is primarily derived from the upper extremities (34). Taylor et al. (36) reported considerable intra-individual variation for the AWC parameter, compared with the CP parameter, utilizing upper-body cycle ergometry. Specifically, the authors (36) suggested that repeated measurements of upper-body AWC may lie between 0.57 to 1.67 times the original measurement. Another study suggested that during combined arm and leg exercise, blood flow to the arms is decrease by 20% than when compared with arm exercise alone in heathy males (38). This significant decrease in blood flow can cause increased accumulation of lactate and hydrogen ions inside the muscles of the arms. Decreases in both intramuscular and serum pH have both been shown to decrease exercise performance capabilities (1, 25). Thus, the greater variability in the ADC parameter in the present study, when compared to the CV, is consistent with the variability reported for performances dependent upon the upper extremities in previous studies (39, 41). Therefore, the non-significant differences and strong relationships between actual and inquired CV and ADC estimates in the present study indicated that individual performance estimations (IT_{con}) from non-standard race distances can be used to derive the parameters of the CV model in experienced, collegiate swimmers.
A third parameter, the time to exhaustion at any velocity greater than CV, can be estimated from the CV model using the equation: predicted time to exhaustion \([PT_{lim}] = \frac{ADC}{(V - CV)}\) (31). Currently, there is conflicting evidence regarding the accuracy of this equation derived from CP and CV model for performance prediction during cycling and running, respectively (8, 18, 33). For example, during cycle ergometry, there were no differences reported between actual \(T_{lim}\) and predicted times to exhaustion \((PT_{lim})\) at power outputs above CP (18). In contrast, significant differences between \(T_{lim}\) and \(PT_{lim}\) at velocities corresponding to 100% and 130% of CV were reported during treadmill running (33). In addition, 800 m track running performance was not accurately estimated from the Linear TD model, despite a significant relationship between the estimated and the actual time to completion. In the present study, the accuracy of the predicted times to completion of \(IET_{com}\) estimated from the \(CV_{inq}\) and \(ADC_{inq}\) parameters was examined for four swimming distances (100, 200, 400, and 800 m). The current findings indicated the CV model over-estimated the \(AT_{com}\) at 100 m (120% of CV). These findings were consistent with previous studies (8, 33) that also reported a tendency for the CV model to over- or under-estimate performance for shorter duration (< 2 minutes), high intensity (>120 – 130% of CV) work bouts. Typically, the work bouts used to derive the parameters of the CV model range from 1 to 10 min; this restricts the slope and allows for the ADC parameter to be estimated with more accuracy (6, 19). In the present study, the mean \(IT_{com}\) values used to derive the parameters of the CV model ranged from 1.5 to 12 min. The mean \(AT_{com}\) at 100 m in the present study was less than one min (55.99 ± 3.47 s) and, thus, \(IET_{com}\) prediction required extrapolation outside the range of values used to derive the CV parameters. Therefore, the limitations of the CV model for
predicting performance outside of the range of values used to derive the CV parameters may have contributed to the significant differences between actual and estimated performance at intensities greater than 120% of CV in the present study as well as previous studies (8, 33).

In the present study, there were no significant mean differences and no significant bias between AT<sub>com</sub> and IET<sub>com</sub> at the distances of 200, 400, and 800 m (Figures 9-12). There were, however, no significant correlations between the mean AT<sub>com</sub> and IET<sub>com</sub> values for any of the distances (Figures 3-6). These findings indicated there was significant intra-individual variability in the IET<sub>com</sub>, compared with the AT<sub>com</sub>. Specifically, at 200 m, the AT<sub>com</sub> was overestimated by a mean (± SD) of 32.01 s (20.08 s) for 6 subjects, and underestimated by 18.21 s (14.91 s) for 8 subjects. At 400 m, the AT<sub>com</sub> was overestimated by at mean value of 38.80 s (31.99 s) for 7 subjects, and underestimated by 48.59 s (38.85 s) for 6 subjects. At 800 m, the AT<sub>com</sub> was overestimated by at mean value of 717.52 s (338.98 s) for 4 subjects, and underestimated by 158.16 s (122.42 s) for 5 subjects. Thus, the tendency for the model to under predict for approximately 50% of the subjects and over predict for the other 50% resulted in mean IET<sub>com</sub> values for the 200, 400, and 800 m that were not different from the AT<sub>com</sub> values. It is possible, that the lack agreement between individual actual and estimated times was related to the high variability inherent of the anaerobic parameter (ADC<sub>inq</sub>) of the CV model. The variability in the ADC<sub>inq</sub> value may have resulted in a greater error in the equation: \( IET_{com} = \frac{ADC}{(V - CV)} \) (36). Therefore, the non-significant mean differences at three distances (200, 400, and 800 m) indicated the model may work for estimating mean responses, however, the lack of correlation and high individual
variability observed between AT_{com} and IET_{com} at these distances suggested the CV model does not provide accurate individual estimations of swimming performance. Thus, the current findings do not support the utilization of the equation, IET_{com} = ADC / (V – CV), for the prediction of individual performance times at intensities greater than CV.

Limitations

The primary limitation of this study was that it relied on self-reported performance times from subjects during their collegiate careers. The individual surveys of inquired performance times were completed while the athletes were in a group. This could have affected the inquired performance times provided by the athletes as they could have discussed their estimates with one another and possibly changed their respective individual estimations based on the responses of their peers. In addition, reported times were unable to be verified through actual trials, as the coaching staff had reservations regarding the impact of the maximal trials on the athletes’ performance in training sessions, as well as competitions.

Future studies should seek to verify self-reported times to completion with actual time trials. This would assist in confirming that subjects’ performance estimations are accurate and may help to explain any significant differences between a subjects’ estimates and actual performance capabilities. In addition, researchers should also attempt to compare the effects of training programs utilizing intensities based on individual derived CV to standard swimming programs used by elite swimmers. Finally, future studies should examine the effects of using a three-parameter model instead of the linear TD model to assess the accuracy of performance predictions as previous studies
have suggested that it may yield more accurate estimates of the CV and ADC parameters in swimmers (42).

**Conclusion**

In conclusion, the high goodness of fit ($r^2 = 0.995$ to 1.000) between TD and $T_{com}$ indicated that the mathematical model used to derive $CV_{ACT}$ and $ADC_{ACT}$ from actual performance times was also applicable to derive the CV parameters ($CV_{inq}$ and $ADC_{inq}$) from inquired swimming performance times. In addition, the CV and ADC parameters derived from actual performance times were not different from those derived from inquired performance times. These findings indicated that the parameters of the CV model can be derived from self-reported performance estimations in collegiate swimmers. The ADC parameter derived from estimated performance times, however, was associated with greater variability ($SE = 30\%$ of the mean) than was the CV parameter ($SE = 5\%$ of the mean). The high variability associated with the ADC parameter in the present study as well as in previous research (36) may have resulted in low accuracy of the performance predictions. Specifically, although there were non-significant mean differences between the actual and predicted performance times at 200, 400, or 800 m, there was no relationship between the two variables for any of the distances (100, 200, 400, or 800m). Thus, the current findings do not support the utilization of the equation, $IET_{com} = ADC / (V – CV)$, for the prediction of individual performance times at intensities greater than CV.

The current findings indicated low accuracy in the performance predictions, however, the CP and CV parameters have been shown to be sensitive to training adaptations (5, 26) as well as to differentiate endurance performance capabilities (23). In
the present study, the CV parameters were accurately estimated from inquired performance times. Thus, the CV derived from inquired performance, rather than performance trials, may be used as a tool for designing individualized training programs in athletes. Specifically, the CV parameter provides an individually derived intensity that may be used to develop training paces within the heavy and severe exercise intensity domains (17) as well as track changes in the fitness level of the swimmer throughout season. The advantage of the model derived from each swimmers inquired performance estimations, rather than performance trials, is that it does not require swimmers to or alter the training routine or training volume.
Chapter IV: Tables

Table 4.1. Subject Demographics (n =14)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (yrs.)</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>19.83</td>
<td>1.67</td>
</tr>
<tr>
<td></td>
<td>Height (cm)</td>
<td>177.08</td>
<td>9.76</td>
</tr>
<tr>
<td></td>
<td>Weight (kg)</td>
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<td>8.34</td>
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Table 4.2. Comparison of Critical Velocity (CV) and Anaerobic Distance Capacity (ADC)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Swimming Experience (yrs.)</th>
<th>CV$_{ACT}$</th>
<th>ADC$_{ACT}$</th>
<th>CV$_{INQ}$</th>
<th>ADC$_{INQ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13</td>
<td>1.449</td>
<td>16.500</td>
<td>1.482</td>
<td>11.280</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>1.404</td>
<td>21.157</td>
<td>1.435</td>
<td>23.640</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>1.454</td>
<td>26.845</td>
<td>1.440</td>
<td>24.815</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>1.581</td>
<td>22.385</td>
<td>1.585</td>
<td>18.482</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>1.480</td>
<td>37.280</td>
<td>1.584</td>
<td>33.882</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
<td>1.563</td>
<td>15.786</td>
<td>1.566</td>
<td>14.790</td>
</tr>
<tr>
<td>7</td>
<td>15</td>
<td>1.501</td>
<td>10.727</td>
<td>1.491</td>
<td>10.222</td>
</tr>
<tr>
<td>8</td>
<td>13</td>
<td>1.417</td>
<td>22.227</td>
<td>1.433</td>
<td>23.074</td>
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<tr>
<td>9</td>
<td>14</td>
<td>1.400</td>
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<td>1.357</td>
<td>26.421</td>
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<tr>
<td>10</td>
<td>10</td>
<td>1.484</td>
<td>29.186</td>
<td>1.513</td>
<td>29.478</td>
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<tr>
<td>11</td>
<td>14</td>
<td>1.432</td>
<td>40.594</td>
<td>1.569</td>
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<tr>
<td>12</td>
<td>10</td>
<td>1.518</td>
<td>19.788</td>
<td>1.417</td>
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<tr>
<td>13</td>
<td>13</td>
<td>1.535</td>
<td>19.886</td>
<td>1.524</td>
<td>23.413</td>
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<tr>
<td>14</td>
<td>12</td>
<td>1.495</td>
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<td>25.307</td>
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<tr>
<td>Mean</td>
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<td>1.480</td>
<td>25.113</td>
<td>1.495</td>
<td>24.874</td>
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<tr>
<td>SD</td>
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<td>8.677</td>
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Table 4.3. Regression Analysis of Actual vs Estimated Values of CV, ADC, and Times to Completion

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>r^2</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV</td>
<td>14</td>
<td>0.371*</td>
<td>0.047 (m/s)</td>
</tr>
<tr>
<td>ADC</td>
<td>14</td>
<td>0.515*</td>
<td>6.525 (m)</td>
</tr>
<tr>
<td>100m T_{com}</td>
<td>14</td>
<td>0.002</td>
<td>3.740 (s)</td>
</tr>
<tr>
<td>200m T_{com}</td>
<td>14</td>
<td>0.097</td>
<td>5.473 (s)</td>
</tr>
<tr>
<td>400m T_{com}</td>
<td>13</td>
<td>0.009</td>
<td>10.741 (s)</td>
</tr>
<tr>
<td>800m T_{com}</td>
<td>9</td>
<td>0.028</td>
<td>18.237 (s)</td>
</tr>
</tbody>
</table>

CV= Critical Velocity; ADC= Anaerobic Distance Capacity; T_{com}= Time to Completion
*Significant coefficient of determination (p < 0.05)
Chapter IV: Figures

Figure 4.1. Relationship between actual Critical Velocity (CV) and Inquired CV

Figure 4.2. Relationship between actual Anaerobic Distance Capacity (ADC) and Inquired ADC
Figure 4.3. Relationship between actual 100 meter time to completion ($T_{\text{com}}$) and $T_{\text{com}}$ derived from the Inquired critical velocity parameters

Figure 4.4. Relationship between actual 200 meter time to completion ($T_{\text{com}}$) and $T_{\text{com}}$ derived from the Inquired critical velocity parameters
Figure 4.5. Relationship between actual 400 meter time to completion ($T_{com}$) and $T_{com}$ derived from the Inquired critical velocity parameters

Figure 4.6. Relationship between actual 800 meter time to completion ($T_{com}$) and $T_{com}$ derived from the Inquired critical velocity parameters
Figure 4.7. Bland-Altman plot showing the mean difference of the Critical Velocity (CV) estimate, which was -0.016±0.056 SD; the slope of regression line was not significant $P = 0.407$; the 95% limits of agreement of the mean difference were -0.125 to 0.094.

Figure 4.8. Bland-Altman plot showing the mean difference of the Anaerobic Distance Capacity (ADC) estimate, which was 0.239±6.807 SD; the slope of regression line was not significant $P = 0.320$; the 95% limits of agreements of the mean difference were -13.103 to 13.581.
Figure 4.9. Bland-Altman plot showing the mean difference of the 100 meter time to completion ($T_{com}$) estimate, which was $-26.459 \pm 20.322$ SD; the slope of regression line was not significant $P = 0.653$; the 95% limits of agreements of the mean difference were -66.290 to 13.372.

Figure 4.10. Bland-Altman plot showing the mean difference of the 200 meter time to completion ($T_{com}$) estimate, which was $-3.317 \pm 30.290$ SD; the slope of regression line was not significant $P = 0.093$; the 95% limits of agreements of the mean difference were -62.685 to 56.051.
Figure 4.11. Bland-Altman plot showing the mean difference of the 400 meter time to completion ($T_{com}$) estimate, which was $1.535\pm56.089$ SD; the slope of regression line was not significant $P = 0.374$; the 95% limits of agreements of the mean difference were -108.399 to 111.469.

Figure 4.12. Bland-Altman plot showing the mean difference of the 800 meter time to completion ($T_{com}$) estimate, which was $-231.034\pm498.730$ SD; the slope of regression line was not significant $P = 0.729$; the 95% limits of agreements of the mean difference were -1208.550 to 746.478.
Figure 4.43. Relationship between all distances (both inquired and actual) and times to completion for subject #1.

\[
y = 1.4735x + 10.722 \\
r = 0.999 \\
r^2 = 0.999 \\
\text{SEE} = 7.674 \\
p < 0.001
\]

Figure 4.14. Relationship between all distances (both inquired and actual) and times to completion for subject #2.

\[
y = 1.4285x + 20.373 \\
r = 0.999 \\
r^2 = 0.999 \\
\text{SEE} = 11.150 \\
p < 0.001
\]
Figure 4.15. Relationship between all distances (both inquired and actual) and times to completion for subject #3.

Figure 4.16. Relationship between all distances (both inquired and actual) and times to completion for subject #4.
Figure 4.17. Relationship between all distances (both inquired and actual) and times to completion for subject #5.

Figure 4.18. Relationship between all distances (both inquired and actual) and times to completion for subject #6.
Figure 4.19. Relationship between all distances (both inquired and actual) and times to completion for subject #7.

Figure 4.20. Relationship between all distances (both inquired and actual) and times to completion for subject #8.
**Figure 4.21.** Relationship between all distances (both inquired and actual) and times to completion for subject #9.

**Figure 4.22.** Relationship between all distances (both inquired and actual) and times to completion for subject #10.
Figure 4.23. Relationship between all distances (both inquired and actual) and times to completion for subject #11.

Figure 4.24. Relationship between all distances (both inquired and actual) and times to completion for subject #12.
Figure 4.25. Relationship between all distances (both inquired and actual) and times to completion for subject #13.

Figure 4.26. Relationship between all distances (both inquired and actual) and times to completion for subject #14.
Figure 4.27. Relationship between all distances (both inquired and actual) and the mean times to completion for all subjects.
Appendix A
Swimming Performance Survey

1. How many years have you been swimming competitively? ___ years

2. How many years have you been swimming at the collegiate level? ___ years

3. What swimming distances would you consider yourself to be the most proficient at?

____________________________________________________________________________

4. What swimming stroke would you consider yourself to be the most proficient at?

____________________________________________________________________________

5. Based on your current abilities, please give your best estimate of your fastest perceived performance times at the following distances, using the front crawl stroke, to the nearest whole second (assuming starting from the block in a 50 meter pool):

   a) 150 meters: _______________________

   b) 350 meters: _______________________
c) 500 meters: _______________________

d) 1100 meters: _______________________

6. Please provide your fastest long course times recorded during a competition, for any of the six distances listed below.

   a) 100 meters: _______________________

   b) 200 meters: _______________________

   c) 400 meters: _______________________

   d) 800 meters: _______________________

   e) 1200 meters: _______________________

   f) 1500 meters: _______________________

7. What is your email address: ________________________________

8. Would you be interested in receiving a free BIA analysis by coming to our lab for a few minutes?               YES / NO
References


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Vita

NAME: Mr. HOWARD BRIM III

EDUCATION

Bachelor of Science, Exercise Science
May 2013
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RESEARCH EXPERIENCE

<table>
<thead>
<tr>
<th>Year</th>
<th>Role/ Principal Investigator</th>
<th>Project</th>
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<tbody>
<tr>
<td>2014 (Summer)</td>
<td>Student Researcher/ Gang Chen, Ph.D</td>
<td>Carcinogenesis induced by Arsenic and UV radiation in mice</td>
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<tr>
<td>2015-2016</td>
<td>Student Researcher/ Gang Chen, Ph.D</td>
<td>Ethanol-induced neurotoxicity in mice</td>
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</table>

PUBLICATIONS

Xu, Wenhua; Hawkey, Andrew; Li, Hui; Dai, Lu; **Brim, Howard**; Handshoe, Jonathan; Frank, Jacqueline; Luo, Jia; Barron, Susan; Chen, Gang. Early Postnatal Ethanol Exposure Causes Behavioral Deficits in Young Mice, manuscript submitted and under review for the journal of *Alcoholism: Clinical and Experimental Research*

SCHOLARSHIPS & FUNDING

August 2009- May 2013  William C. Parker Diversity Scholarship, University of Kentucky

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