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A Non-Exercise Based Estimation of the Critical Running Velocity and Anaerobic Running Capacity in Competitive Runners

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A NON-EXERCISE BASED ESTIMATION OF THE CRITICAL RUNNING VELOCITY AND ANAEROBIC RUNNING CAPACITY IN COMPETITIVE RUNNERS

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

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2016

ABSTRACT OF THESIS

A NON-EXERCISE BASED ESTIMATION OF THE CRITICAL RUNNING VELOCITY AND ANAEROBIC WORK CAPACITY IN COMPETITIVE RUNNERS

This study examined: 1) if estimated performance times (ET_{com}) at four different distances can be used to accurately define the parameters of the critical velocity (CV) test [CV and anaerobic running capacity (ARC)]; and 2) if those parameters can be used to predict time to completion (PT_{com}) of distances performed at velocities greater than CV. Twelve subjects provided an ET_{com} for maximal-effort runs at 400m, 800m, 1600m, and 3200m. The CV and ARC were derived from the total distance (TD) versus ET_{com} relationship. The equation: PT_{com} = ARC / (velocity-CV) was used to determine the PT_{com} for runs at 200m, 600m, and 1000m. The PT_{com} was validated against the actual time to complete (AT_{com}) runs at the same three distances. The TD versus ET_{com} relationship was highly linear and indicated a close relationship between running distance and time. The PT_{com} overestimated the AT_{com} at 200m, but was not different from AT_{com} at 600m and 1000m. The PT_{com} and AT_{com} were not related at any of the three distances. The CV model could be applied to estimated performance times to derive the CV and ARC parameters, but the parameters of the test did not accurately estimate performance times above CV.

____Jonathan Robert Switalla_______

_________August 29, 2016__________

A NON-EXERCISE BASED ESTIMATION OF THE CRITICAL RUNNING VELOCITY AND ANAEROBIC WORK CAPACITY IN COMPETITIVE RUNNERS

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Chapter I: Introduction

The critical power (CP) concept, was originally developed by Monod and Scherrer (1965) to examine the relationship between the total amount of work performed (W_{lim}) and the time to exhaustion (T_{lim}) from a series of three to four exhaustive, intermittent isometric and dynamic muscle actions. Moritani et al. (1981) applied the CP concept to cycle ergometry. For this test, the total amount of work was plotted against the T_{lim} for a series of three to four exhaustive constant power output rides. The CP was defined as the slope of the W_{lim} versus T_{lim} relationship and, theoretically, represented the highest power output that could be maintained without exhaustion. The anaerobic work capacity (AWC) was defined as the y-intercept and represented the total work performed above CP using only stored energy sources within the active muscle. The authors (Moritani et al. 1981) also suggested that the T_{lim} for any power output greater than CP could be predicted (T_{lim} = AWC / (P – CP)). Hughson et al. (1984) examined the applicability of the CP concept for cycle ergometry to treadmill running to derive the critical velocity (CV) and anaerobic running capacity (ARC). The authors (Hughson et al. 1984) observed the same hyperbolic relationship between velocity and T_{lim} that had previously been shown for P versus T_{lim} relationship during cycle ergometry. Based on these findings, the authors (Hughson et al. 1984) concluded that the CP concept was applicable to treadmill running to derive the CV and ARC.

It has been suggested (Poole et al. 1988) that CP/CV demarcate the heavy from severe exercise intensity domains. The severe domain is defined by exercise intensities that cause $\dot{V}O_2$ and blood lactate to increase until exhaustion, whereas exercise performed within the heavy domain results in a delayed steady state for both $\dot{V}O_2$ and blood lactate.

Previous studies have examined physiological responses to exercise performed above, below, and at CP/CV to determine the validity of CP/CV as the demarcation of the heavy and severe exercise intensity domains. For example, Poole et al. (1988) reported that exercise performed at 5% above CP resulted in exhaustion within 24 min for all but one subject. In addition, the authors (Poole et al. 1988) reported continuous increases in $\dot{V}O_2$ and blood lactate responses during exercise performed above CP. At CP, however, all of the subjects were able to maintain exercise for at least 24 min and the $\dot{V}O_2$ and blood lactate responses reached steady state values. Thus, the authors (Poole et al. 1988) concluded that, during constant power output rides performed at power outputs above CP, the subjects will reach exhaustion within 20 min and $\dot{V}O_2$ will continue to increase until $\dot{V}O_{2max}$ is reached. Based on these findings it was suggested (Poole et al. 1988) that CP represents the demarcation of the heavy from severe exercise intensity domains. In contrast, Brickley et al. (2002) reported that, although exercise at CP did not result in an increase in oxygen consumption to the maximal level attained when the subjects performed the incremental ramp protocol, it did not reach a steady state. In addition, the authors (Brickley et al. 2002) reported exercise at CP resulted in exhaustion between 20 and 40 min. Therefore, the authors (Brickley et al. 2002) suggested CP did not represent a sustainable steady-state intensity of exercise. Thus, there is conflicting evidence (Poole et al. 1988, Brickley et al. 2002) regarding the ability of CP/CV parameters to identify the highest sustainable exercise intensity and the demarcation the heavy from severe domains.

Previous studies (Dekerle et al. 2006; Hill and Smith 1993; Nebelsick-Gullet et al. 1988) have examined the validity of the AWC parameter of the CP test. For example, Dekerle et al. (2006) compared the curvature constant parameter (W'), derived from the hyperbolic power-time (P-t) relationship, with the amount of work performed above critical power (W_{90s}') and AWC from the linear W_{lim} versus T_{lim} relationship. The authors (Dekerle et al. 2006) found that W' underestimated the anaerobic capacity (AC) and that the difference between AWC and W' and between AWC and W_{90s}' were inversely correlated to $\dot{V}O_{2max}$. Thus, the authors (Dekerle et al. 2006) concluded that W', W_{90s}', and AWC cannot be used interchangeably. Hill and Smith (1993) examined the relationship between AC, determined from the nonlinear power-time relationship, and the maximal oxygen deficit during constant power exercise. The authors (Hill and Smith 1993) reported no significant difference in the estimate of AC (the curvature constant parameter [W']) between trial 1 and trial 2. There was also no difference in the estimated maximal oxygen deficit between trial 1 and trial 2. Finally, the authors determined that AC can be accurately estimated by the W' parameter of nonlinear power-time relationship during high-intensity exercise. Nebelsick-Gullet et al. (1988) examined the validity of AWC from the CP test as an indirect measure of anaerobic capabilities. The authors (Nebelsick-Gullet et al. 1988) reported a significant correlation between the AC calculated from the Wingate test and AWC from the work limit versus time limit relationship of the CP test. Therefore, the results of previous studies (Dekerle et al. 2006; Hill and Smith 1993; Nebelsick-Gullet et al. 1988) indicate the CP test provides a valid and reliable estimation of anaerobic capabilities.

Researchers have also examined the accuracy of CP to predict time to exhaustion. Pepper et al. (1992) indicate the CV model accurately predicted the time to exhaustion at 85 and 115% of CV, but it over predicted at 100 and 130%. Housh et al. (1989), however, reported that time to exhaustion was accurately predicted at power outputs above CP, during cycle ergometry using the equation T_{lim} =AWC / (P – CP). Thus, the results of previous studies (Housh et al. 1989, Pepper et al. 1992) indicate there is conflicting evidence regarding the ability of the CP/CV model to provide an accurate estimate of the subjects' performance capabilities at power loadings greater than CP or CV.

Typically, the CP and CV test parameters are determined from multiple, constant power output or velocity work bouts, performed to exhaustion. The W_{lim} or total distance (TD) is then plotted against the T_{lim} to derive CP/CV and AWC/ARC. Recently, Black et al. (2015) examined the effect of pacing strategy during severe-intensity prediction trials on the CP and $\dot{V}O_2$ mean response time. The authors (Black et al. 2015) found that the CP derived from the time-trials protocol was greater than the CP derived from the constant work rate protocol, while the $\dot{V}O_2$ mean response time was shorter during the time-trials than the constant work rate trials. Black et al. (2015) suggested that, in comparison with the conventional constant work rate protocol, a self-selected pacing strategy improves CP and therefore improves severe-intensity exercise performance. These findings (Black et al. 2015) indicate performance variables, rather than times to exhaustion, may provide accurate estimates of the CP test parameters. No previous studies, however, have examined the validity of CV and ARC derived from estimated performance capabilities at predetermined distances during track running.

The CP test is physically demanding, requiring multiple, exhaustive work bouts. To improve the applicability of the test, previous studies have examined the number of trials necessary to accurately estimate CP. Burnley et al. (2006) developed a 3-min all-out test in an attempt to identify the maximal power output where steady state responses can be achieved. The authors (Burnley et al. 2006) reported that power output plateaued during the final 30 seconds of the test. The average power output over the final 30 s of the test was defined as the end-test power, and hypothesized to represent the maximal power output where metabolic parameters would reach a steady state. The authors (Burnley et al. 2006) reported that none of the subjects were able to maintain 30 min of exercise above the end-test power and $\dot{V}O_2$ and blood lactate increased until exhaustion. During exercise below the end-test power $\dot{V}O_2$ and blood lactate eventually stabilized, and 9 out of the 11 subjects were able to complete 30 min of exercise. Thus, the authors suggested that the end-test power provided a demarcation of heavy from severe exercise intensities and the 3-min bout of all-out exercise represented a promising method of estimating the maximal steady state. Vanhatalo et al. (2007) compared the parameters of the power-duration relationship derived from a 3-min all-out cycling test with those derived from the linear relationship between total work and time to exhaustion from a series of five different constant power output rides. Vanhatalo et al. (2007) demonstrated that the end-power in a 3-min all-out cycling test was not significantly different from CP, and the work done above end-test power (WEP; the integral of the power output versus time relationship above end-test power) was found to be similar to the curvature constant parameter (AWC). The authors (Vanhatalo et al. 2007) suggested that the 3-min all-out test could provide estimates of both CP and AWC.

The 3-min all-out test reduced the number of work bouts necessary to estimate CP and AWC, however, two exhaustive work bouts were required to complete the testing. A graded exercise test with the measurement of gas exchange parameters was required to determine the resistance setting for the 3-min all-out test. Thus, it was not truly a single work bout test. Therefore, Bergstrom et al. (2012) attempted to further simplify the protocol for the 3-min all-out test using a mechanically braked cycle ergometer, with the resistance based on body weight. The authors (Bergstrom et al. 2012) reported that CP and AWC, estimated from a 3-min all-out test with the resistance set at 4.5% of body weight, were not different than the estimates derived from the multiple work bout model. These findings (Bergstrom et al. 2012) indicated that CP and AWC could be estimated from a single, 3-min all-out test with the resistance set at 4.5% of the subject's body weight.

Although a single, 3-min all-out test may be more practical than performing multiple work bouts to determine CP and AWC, many athletes and coaches do not have access to the necessary equipment and may not be willing to alter training schedules to complete the test. A protocol that utilizes estimated performance times to determine the parameters of the CV model would improve the applicability of the test. Therefore, the purposes of this study were to determine: 1) if estimated performance times at four different distances can be used to accurately define the parameters of the CV test (CV and ARC); and 2) if those parameters can be used to estimate PT_{com} for distances performed at velocities greater than CV, using the equation $PT_{com} = ARC / (V – CV)$. We hypothesized that: 1) CV and ARC would be accurately estimated from a non-exercise based protocol utilizing estimated performance times; and 2) the equation ($PT_{com} = ARC / (V – CV)$) will accurately estimate performance at velocities greater than CV.

Chapter II: Review of Literature

1. Development of the Critical Power Concept

Monod and Scherrer (1965)

The purposes of the study were to: 1) examine the amount of work a muscle can perform before exhaustion; and 2) identify the conditions of a fatigueless task during intermittent isometric, isometric, and dynamic local muscular work. Local muscular work was defined as work that "… can be performed by less than one-third of the whole muscular mass" (p. 329). The authors examined the relationship between the total amount of work (W_{lim}) performed and the time to exhaustion (T_{lim}) during three constant power output (P) trials. A mathematical model was used to linearly relate the W_{lim} and T_{lim} and was described by the equation $W_{lim} = a + b\ (T_{lim})$. The authors identified three separate parameters from this mathematical model: 1) critical power (CP) was the slope (b) of the W_{lim} versus T_{lim} relationship and was defined as "… the maximal rate (a muscle) can keep up for a very long time" (p. 329); 2) anaerobic work capacity (AWC) was the y-intercept (a) and represents the total work performed above CP using only stored energy sources within the active muscle; and 3) the estimated T_{lim} for any P greater than CP using the following equation: $T_{lim} = a / (P – CP)$.

Moritani et al. (1981)

The purposes of this study were to: 1) test whether the critical power (CP) concept could be extended to whole-body exercise; and 2) determine if CP was related to the anaerobic threshold (AT) and the $\dot{V}O_2$max. This study used eight male and eight female college students (18-33). The $\dot{V}O_2$max was determined from an incremental (25 W·min^{-}

[1]) test to exhaustion on a cycle ergometer. The subjects performed three to four exhaustive, constant power output rides on a cycle ergometer. The time to exhaustion (T_{lim}) was recorded and the total amount of work (W_{lim}) was calculated (power output x T_{lim}) for each exhaustive constant power output ride. The W_{lim} was plotted against T_{lim} and described by the equation $W_{lim} = a + b(T_{lim})$. The CP was defined as the slope of the W_{lim} versus T_{lim} relationship, and the AWC was the y-intercept. The authors also determined that T_{lim} could be predicted for any power output above CP. Significant correlations were reported among the $\dot{V}O_2$ and power outputs associated with the AT, CP, and $\dot{V}O_{2peak}$ ($r = 0.870$-0.927, $p < 0.01$). Critical power was found to represent the power output that a muscle group can maintain without exhaustion. The authors concluded, that when the required power output approaches very close to CP the work may be theoretically continued almost indefinitely. Thus, $P(T_{lim}) = AWC + CP(T_{lim})$, so $T_{lim} = (AWC) / (P - CP)$.

Hughson et al. (1984)

The purpose of the study was to examine whether the hyperbolic relationship that occurs between power output and time to exhaustion (T_{lim}), can also be shown between velocity and time to exhaustion during treadmill running to derive the critical running velocity (CV). This study used six male collegiate cross-country runners (age = 19-22 yr, height = 172-191 cm, weight = 55-79.2 kg, $\dot{V}O_2max$ = 65-73 $ml \cdot kg^{-1} \cdot min^{-1}$). During the test, a total of six runs were performed at different velocities with the intensity set high enough to result in exhaustion between 2-12 minutes. The testing days were separated by at least 48 hours. The velocity was plotted against the T_{lim} to determine the hyperbolic relationship between velocity and T_{lim}. The treadmill velocity was also plotted against the inverse of T_{lim}. The relationship between velocity and the inverse of T_{lim} was highly linear (r = 0.979 to 0.997) which suggested the hyperbolic model to the velocity-endurance time relationship was applicable to treadmill running. In addition, the authors showed the relationship between velocity and T_{lim} could be used to predict the T_{lim} for a specified distance. Based on these findings, and the high correlation between CV and $\dot{V}O_{2max}$ (r = 0.84) the authors concluded that the CV described the attribute of the aerobic energy supply system.

Summary:

The critical power (CP) concept, was originally developed by Monod and Scherrer (1965) to examine the relationship between the total amount of work performed (W_{lim}) and the time to exhaustion (T_{lim}) for a series of three to four exhaustive, intermittent isometric and dynamic muscle actions. Moritani et al. (1981) applied the CP concept to cycle ergometry. For this test, the total amount of work was plotted against the T_{lim} for a series of three to four exhaustive constant power output (P) rides. The CP was defined as the slope of the W_{lim} versus T_{lim} relationship and, theoretically, represented the highest power output that could be maintained without exhaustion. The anaerobic work capacity was defined as the y-intercept and represented the total work performed above CP using only stored energy sources within the active muscle. The authors (Moritani et al. 1981) also suggested that the T_{lim} for any P greater than CP can be predicted ($T_{lim} = a / (P – CP)$). Hughson et al. (1984) examined the applicability of the CP concept for cycle ergometry to treadmill running to derive the critical velocity (CV).

The authors (Hughson et al. 1984) observed the same hyperbolic relationship between velocity and T_{lim} that had previously been shown for P versus T_{lim} relationship during cycle ergometry. Based on these findings, the authors (Hughson et al. 1984) concluded that the CP concept was applicable to treadmill running to derive the CV.

2. The Critical Power Parameter

2.1 Physiological responses during rides to exhaustion above, below, and at Critical Power

Poole et al. (1988)

The purpose of this study was to investigate the metabolic and respiratory responses over time during prolonged, constant power output cycle ergometry exercise at and above the critical power (CP). Eight males, none of which were involved in regular physical training, were involved in this study (age = 22 ± 1 yr, weight = 75.6 ± 4.8 kg, height = 175.5 ± 7.4 cm). The test consisted of incremental and square-wave exercise tests on an electromagnetically braked cycle ergometer. Only one test was performed on a given day and the sequence was randomized. Each subject performed an incremental test (25 W min^{-1}) to exhaustion for the estimation of lactate threshold and $\dot{V}O_{2max}$. The subjects were not aware of the duration or power output during the cycle ergometry tests. The total amount of work (W_{lim}) and time to exhaustions (T_{lim}) were recorded for each of the square wave bouts. The anaerobic work capacity (AWC) was defined as the slope of the W_{lim} versus inverse of T_{lim} relationship and the y-intercept was the CP. The CP (69% of max power output) was greater than the lactate threshold for all of the subjects, averaging 164% of the lactate threshold. The subjects performed two constant power output tests at the CP and +5% CP. Each test was maintained for 24 minutes or to exhaustion. All of the subjects completed 24 min of exercise at CP and $\dot{V}O_2$ and the blood lactate concentration reached steady state values. At +5% CP, all but one of the subjects exhausted prior to 24 min (average duration 17.7 ± 1.2 min) and $\dot{V}O_2$ and the blood lactate concentration increased throughout the constant-load test . The authors concluded that during constant-load exercise tests performed at power outputs above the power asymptote of the power-time relationship, $\dot{V}O_2$ will continue to increase eventually attaining a maximum $\dot{V}O_2$ and the limit of work tolerance.

G. Brickley et al. (2002)

The purpose of the study was to examine the physiological responses to exercise at critical power (CP). Seven trained males, familiar with cycle ergometry (mean age 23.4 ± 3.1 years), completed five exercise tests: an incremental ramp protocol test to determine $\dot{V}O_{2max}$; three constant load tests (time to exhaustion = 1 to 10 min) to determine CP, and a final test to exhaustion at CP. At least 24 hours of rest was given between tests, and all the tests were completed within 14 days. CP was defined as the slope of the highly linear ($r^2 = 0.985$) relationship between the total work versus time to exhaustion from the three constant load tests. The time to failure for the rides at CP ranged from 20 minutes 1 second to 40 minutes 37 seconds. It was found that after 20 minutes, oxygen consumption increased from a mean value of 3.7 $L \cdot min^{-1}$ up to 4.13 $L \cdot min^{-1}$, while the mean heart rate increased from 120 $b \cdot min^{-1}$ to 178 $b \cdot min^{-1}$. The subjects' heart rate at exhaustion averaged 186 $b \cdot min^{-1}$. The time to failure was significantly correlated with final oxygen uptake ($r = 0.69$, $P < 0.05$), as was CP ($r = 0.92$, $P < 0.05$). $\dot{V}O_{2max}$ was significantly correlated with time to exhaustion ($r = 0.78$, P <

0.05). Although exercise at CP did not result in an increase in oxygen consumption to the maximal level attained during the incremental ramp protocol, CP did not represent a sustainable, steady-state intensity of exercise.

A. Bull et al. (2000)

The purpose of this study was to examine the electromyographic (EMG) and mechanomyographic (MMG) amplitude responses during continuous cycle ergometry at critical power (CP) estimated from the three parameter, nonlinear regression model (Nonlinear-3) of Morton et al. (1996). The subjects consisted of seven moderately active adult males (mean age, 25 ± 3 years) each participating in general resistance training and moderate aerobic training programs. Seven or eight exercise trials were completed with ≥ 24 hours separating each trial. The first visit involved a maximal incremental test to exhaustion on an electronically braked cycle ergometer to determine the peak power (P_{peak}). Five or six randomly ordered trials at power outputs, ranging from P_{peak} -130 W to P_{peak} +50 W, were used for the estimation of CP. If the subject did not complete at least 10 min of cycling during any of the first five trials, the subject performed a sixth trial at a lower power output. Each subject's CP was determined by fitting the power output (P) and time to exhaustion (T_{lim}) data to the Nonlinear-3 model. The subject then completed a 60-min trial at their CP estimated from the Nonlinear-3 model. Generalized least squares (GLS) regression analyses were used to determine the relationships for EMG and MMG amplitudes versus time. There was no change across time in EMG amplitude, but significant decrease in the mean MMG amplitude during the 60-min rides at CP. The lack of increase in EMG amplitude suggested there was no change in motor unit activation during the continuous ride at CP, while the decrease in MMG amplitude was attributed to the effects of muscle wisdom and/or decreases in muscular compliance. The authors suggested these findings supported the hypotheses that CP demarcates heavy-intensity from severe-intensity exercise and that the slow component of $\dot{V}O_2$ kinetics may be mediated by fatigue-induced recruitment of additional motor units.

2.2 Comparison of Critical Power to Other Fatigue Thresholds

deVries et al. (1982)

The purpose of this study was to determine the relationship between critical power (CP) and electromyographic fatigue threshold (EMG_{FT}) during cycle ergometry. The authors hypothesized that: 1) CP would be closely related to the onset of neuromuscular fatigue as estimated in the EMG_{FT}; and 2) both of these measures would be correlated with the anaerobic threshold. The subjects consisted of five men and six women between 19 and 32 years. Critical power was determined from a series of four different constant power output rides to exhaustion. The time to exhaustion (T_{lim}) was recorded and the total amount of work performed (W_{lim}) was calculated (Power output x T_{lim}). Critical power was defined as the slope of the relationship between W_{lim} versus T_{lim}. The EMG_{FT} was determined from the four constant power output rides. The EMG amplitude was plotted against time for each power output. The power output was then plotted against the slope coefficient of the EMG amplitude versus time relationship, and the y-intercept was defined as the EMG_{FT}. The anaerobic threshold was determined from an incremental cycle ergometer test and defined as the breakpoint in the minute ventilation ($\dot{V}_E$) versus $\dot{V}O_2$ relationship. The findings indicated the power output at the EMG_{FT} was greater than CP, but the two thresholds were highly correlated. The EMG_{FT}

and CP, however, were not different from the anaerobic threshold. All fatigue thresholds were highly correlated. The authors concluded that, although they occur at slightly different power outputs, a common mechanism likely underlies CP, the EMG_{FT}, and the anaerobic threshold.

McLellan and Cheung (1992)

The purpose of the study was to evaluate the metabolic and cardiorespiratory responses at the power outputs that represented individual anaerobic threshold (IAT) and critical power (CP). This study consisted of fourteen healthy males (age: 23.4 ± 3.7 yr), seven of which were trained cyclists and seven were regularly active students. Each exercise session took place at the same time of day and tests were performed at least 4 h postprandial. Each of the subjects completed 10 exercise tests, which were performed at weekly intervals except for the CP determination tests, which were performed no less than 48 h apart. All of the testing was performed on an electrically braked cycle ergometer. The $\dot{V}O_{2max}$ and IAT were determined from a maximal incremental exercise test. The resistance settings for the CP consisted of five power outputs that corresponded to 90, 95, 100, 110, and 120% of $\dot{V}O_{2max}$ for each subject. The power outputs were selected so the exercise time to exhaustion would occur between 2 and 15 min. The power output was plotted against the inverse of the time to exhaustion and CP was defined as the y-intercept. The subjects performed exercise tests at the power outputs defined as the IAT and CP for a maximum of 30 min or until exhaustion. The results showed that the blood lactate levels were higher during the ride at CP compared with IAT, and increased at a faster rate. The pH and PCO_2 values showed a greater decrease during the exercise period at CP. The authors concluded that the methods used to determine CP overestimated the power output associated with a maximal steady-state blood lactate and acid-base response. The findings also indicate the IAT slightly over- or underestimated the power output associated with a maximal steady-state blood lactate and acid-base response.

2.3 Accuracy of the Time to Exhaustion Prediction from the Critical Power Model

Pepper et al. (1992)

The purpose of this study was to determine the accuracy of the equation TL = ARC / (v – CV), where TL is time limit; ARC is anaerobic running capacity; v is velocity; and CV is critical velocity, from the CV test for predicting the actual TL during treadmill running. Ten male subjects were involved in this study (age: 23 ± 2 years). The subjects first completed a continuous incremental treadmill test to exhaustion to determine their maximal oxygen consumption or $\dot{V}O_{2max}$. Four, randomly ordered treadmill runs to exhaustion at velocities ranging from 12.88 to 21.74 $km \cdot h^{-1}$ were used to estimate CV. The equation TL = ARC / (v – CV) was derived from the linear regression of the total distance versus time to exhaustion. The accuracy of the equation TL = ARC / (v – CV) to predict the actual time to exhaustion was examined during five, randomly ordered treadmill runs at velocities approximately equal to 70, 85, 100, 115, and 130% of CV. The tests were terminated when the subjects' reached for the handrails or completed 60 minutes. The results from the study showed there were no significant differences between the predicted and actual TL values for the velocities representing approximately 85% and 115% of CV, but significant differences did exist between the predicted and actual TL values for the velocities representing 100% and 130% of CV. For the five treadmill runs, only eight of the ten subjects completed the 60-minute work bout at 85%, the other two subjects completed 35.00 min and 36.13 min. There was no significant difference between CV and the velocity corresponding to $\dot{V}O_{2max}$, and they were highly correlated. These findings indicate that the equation TL = ARC / (v – CV) accurately predicted the actual TL at 85% and 115% of CV, but over predicted TL at CV by 265% and under predicted TL at 130% of CV by 8%. These findings did not support the validity of the TL = ARC / (v – CV) equation for predicting the time to exhaustion.

Housh et al. (1989)

The purpose of this study was to compare the predicted time to exhaustion (PT_{lim}) to the actual T_{lim} (AT_{lim}) during cycle ergometery using the critical power (CP) model. The subjects involved in the study were fourteen males (age: 22.36 ± 2.13 yrs). The subjects visited the lab on seven different occasions. The first two visits were for the determination of CP and the last five were to determine the subject's AT_{lim} at five different power loadings on a Monark cycle ergometer. All of the visits were separated by greater than 24 hours. For the determination of CP, the subjects performed four dynamic exercise bouts with the power loadings ranging from 172 - 360 W. Two power loadings were performed per day. The total work was plotted against T_{lim} from the four constant power output tests. The regression equation from the total work versus T_{lim} relationship was used to derive the equation PT_{lim} = AWC / (p – CP). The PT_{lim} was compared to the AT_{lim} from five randomly ordered, constant power output rides at CP - 20%, CP, CP +20%, CP +40%, and CP +60% to determine the accuracy of the PT_{lim}.

The results showed no significant differences between the PT_{lim} and AT_{lim} at the power loadings above CP, but at CP -20% only 13 of the 14 subjects were able to complete a 1 h work-bout. The authors concluded that the equation T_{lim} = AWC / (p – CP) from the CP test provided an accurate estimate of the subjects' muscular working capacities at power loadings greater than CP, but the CP estimate was approximately 17% greater than the power loading which could be maintained for 60 minutes.

Summary:

Previous studies have also examined physiological responses to exercise performed above, below, and at CP. For example, Poole et al. (1988) reported that exercise performed at 5% above CP resulted in exhaustion for within 24 min for all but one subject, but all subjects were able to maintain exercise for at least 24 min during exercise at CP. In addition, the authors (Poole et al. 1988) reported continuous increases in $\dot{V}O_2$ and blood lactate responses during exercise performed above CP. At CP, however, the $\dot{V}O_2$ and blood lactate responses reached a steady state value. Thus, the authors (Poole et al. 1988) concluded that, during constant-load exercise tests performed at power outputs above the power asymptote of the P-t relationship, $\dot{V}O_2$ will continue to increase eventually attaining a maximum $\dot{V}O_2$ and the limit of work tolerance. It was suggested (Poole et al. 1988) that CP represents the demarcation of the heavy from severe exercise intensity domains. Brickley et al. (2002) reported that exercise at CP did not result in an increase in oxygen consumption to the maximal level attained when the subjects performed the incremental ramp protocol, but did not reach a steady state. In addition, the authors reported exercise at CP resulted in exhaustion between 20 min 1 sec to 40 min 37 sec. Therefore, the authors (Brickley et al. 2002) suggested CP did not represent a sustainable steady-state intensity of exercise. Bull et al. (2000) examined the electromyographic (EMG) and mechanomyographic (MMG) responses during continuous cycle ergometry at CP, derived from the three parameter non-linear model. The authors (Bull et al. 2002) reported no change across time in EMG amplitude (which reflects motor unit activation), but a significant decrease in the mean MMG amplitude (reflecting potential effects of muscle stiffness) during the 60-min ride at CP. Based on these findings, the authors (Bull et al. 2002) suggested that CP demarcates heavy-intensity from severe-intensity exercise and that the slow component of $\dot{V}O_2$ kinetics may be mediated by fatigue-induced recruitment of additional motor units. Based on the findings, the authors (Poole et al. 1988; Brickley et al. 2002; Bull et al. 2002) conclude that CP demarcates heavy-intensity exercise from severe-intensity exercise.

The critical power (CP) parameter has been compared to other fatigue thresholds, such as the anaerobic threshold and electromyographic fatigue threshold (EMG_{FT}). For example, deVries et al. (1982) examined the relationship between the anaerobic threshold (AT), CP, and the onset of neuromuscular fatigue, estimated from EMG_{FT}. The findings (deVries et al. 1982) indicate the power output at the EMG_{FT} was greater than CP, but the two thresholds were highly correlated. The EMG_{FT} and CP, however, were not different from the anaerobic threshold. All fatigue thresholds were highly correlated. The authors concluded that, although they occur at slightly different power outputs, a common mechanism likely underlies CP, the EMG_{FT}, and the anaerobic threshold. McLellan and Cheung (1992) evaluated the metabolic and cardiorespiratory responses at the power outputs that represented individual anaerobic threshold (IAT) and CP. The authors found the methods used to determine CP overestimated the power outputs associated with steady-state blood lactate and acid-base response, while the calculated IAT slightly over- or underestimated the actual power output associated with the steady-state blood lactate and acid-base response. In conclusion, deVries et al. (1982) and McLellan and Cheung (1992) found that there is probably a common mechanism that likely underlies CP and AT.

Researchers have also examined the accuracy of critical power to predict time to exhaustion. Pepper et al. (1992) indicated the CV model accurately predicted the time to exhaustion at 85 and 115% of CV, but it was over predicted at 100 and 130%. Housh et al. (1989), however, reported that time to exhaustion was accurately predicted during cycle ergometry using the equation $T_{lim} = AWC / (P – CP)$. The authors concluded that the equation from the CP test provided an accurate estimate of the subjects' muscular working capacities at power loadings greater than CP. Therefore, Pepper et al. (1992) and Housh et al. (1989) found that CP accurately predicts time to exhaustion.

3. The Anaerobic Work Capacity Parameter

Dekerle et al. (2006)

The purpose of the study was to compare the curvature constant parameter (W') derived from the hyperbolic power-time (P-t) relationship with the amount of work performed above critical power (W_{90s}') and anaerobic work capacity (AWC), both determined from a 90s all-out test. Fourteen subjects volunteered for this study (10 male and 4 female; age: 30.5 ± 1.7 years; weight: 67.8 ± 2.7 kg; $\dot{V}O_{2max}$: 3.9 ± 0.7 $l \cdot min^{-1}$). The study consisted of three stages of experimentation. Stage 1) involved the determination of the maximum oxygen uptake ($\dot{V}O_{2max}$) and its corresponding power output (P-$\dot{V}O_{2max}$), stage 2 involved three constant-load tests (one test per session) to exhaustion to determine the critical power (CP) and W', and stage 3 involved two, 90s all-out efforts to determine W_{90s}' and AWC. The constant load tests and 90s all-out tests were separated by at least two days. The authors reported that W' derived from the critical power trials and W_{90s}' derived from the 90s all-out test were not significantly different (P = 0.96). The AWC derived as the integrated difference between the actual and equivalent power of the 90s all-out test was significantly greater than both measures (P = 0.03 and P = 0.04). The W' and AWC, W' and W_{90s}', and W_{90s}' and AWC were all significantly correlated (P < 0.001). The non-significant difference between W' and W_{90s}' was consistent with the authors hypothesis that the total amount of work performed above CP during a 90s all-out test is not significantly different from that predicted from establishing the curvature constant of a standard P-t relationship.

<u>Hill and Smith (1993)</u>

The purpose of this study was to determine the validity of anaerobic capacity determined from the nonlinear power-time relationship with the maximal oxygen deficit during constant power exercise. Twenty-six subjects completed this study, 13 women (age: 23 ± 2 years) and 13 men (age: 23 ± 2 years). The subjects performed five, high-intensity cycling exercise bouts to exhaustion. Each of the tests took place on a different day and at a different relative power. Oxygen deficit was determined during each test and the mean of the two oxygen deficits from the power output that elicited the highest values was taken as the criterion measure of anaerobic capacity. The anaerobic capacity was estimated from the hyperbolic power-time relationship for each set of five data points. Four of the tests were performed at pre-determined power outputs and the fifth was determined based on the response to the first four trials. The authors reported no significant difference in the estimate of anaerobic capacity (the curvature constant parameter [W']) between trial 1 and trial 2. There was also no difference in the estimated maximal oxygen deficit between trial 1 and trial 2. In addition, there was a strong correlation between the two estimates of anaerobic capacity. The authors indicate anaerobic capacity can be accurately estimated by the W' parameter of the nonlinear power-time relationship during high-intensity exercise.

Nebelsick-Gullett et al. (1988)

The purposes of the study were to: 1) determine the validity of anaerobic work capacity (AWC) from the critical power (CP) test as an indirect measure of anaerobic capabilities; and 2) to determine the test-retest reliability of the CP test. Twenty-five moderately (exercise 2-3 days per week) to highly (exercise 5-7 days per week) trained females (age: 19 to 27 years) volunteered for this study. The anaerobic capacity (AC) was estimated from the Wingate anaerobic test (WAnT). The AC was defined as the total amount of work performed during the 30-second work bout of the WAnT. The subjects then performed three dynamic exercise bouts at power loadings ranging from 156 to 313 watts on a Monarck ergometer. The work limit (WL) for each exercise bout was calculated by multiplying power output and time limit (TL). The AWC was the amount of work corresponding to the Y intercept of the WL-TL relationship, while critical power was the power output corresponding to the slope of the WL-TL relation. The reliability of CP and AWC was determined by test-retest procedures, which were performed by all subjects, one to seven days apart. The authors found that for all subjects a highly linear relationship occurred between WL and TL. The authors concluded that the CP test provides a valid and reliable estimation of anaerobic capabilities as well as the maximal rate of fatigueless work.

Summary:

Previous studies (Dekerle et al. 2006; Hill and Smith 1993; Nebelsick-Gullet et al. 1988) have examined the validity of the anaerobic work capacity (AWC) parameter of the critical power (CP) test. For example, Dekerle et al. (2006) compared the curvature constant parameter (W'), derived from the hyperbolic P-t relationship, with the amount of work performed above critical power (W_{90s}') and anaerobic work capacity (AWC). The authors found that W' underestimates the anaerobic capacity and that the difference between AWC and W' and between AWC and W_{90s}' were inversely correlated to $\dot{V}O_{2max}$. Hill and Smith (1993) examined the relationship between anaerobic capacity, determined from the nonlinear power-time relationship, and the maximal oxygen deficit during constant power exercise. The authors (Hill and Smith 1993) reported no significant difference in the estimate of anaerobic capacity (the curvature constant parameter [W']) between trial 1 and trial 2. There was also no difference in the estimated maximal oxygen deficit between trial 1 and trial 2. Finally, the authors determined that anaerobic capacity can be accurately estimated by the W' parameter of nonlinear power-time relationship during high-intensity exercise. Nebelsick-Gullet et al. (1988) conducted a similar study examining the validity of AWC from the critical power test as an indirect measure of anaerobic capabilities. The authors (Nebelsick-Gullet et al. 1988) reported a significant correlation between the anaerobic capacity calculated from the Wingate test and AWC from the work limit versus time limit relationship of the CP test. Therefore, the results of previous studies (Dekerle et al. 2006; Hill and Smith 1993; Nebelsick-Gullet et al. 1988) indicate the CP test provides a valid and reliable estimation of anaerobic capabilities.

4. Protocol Variations in the Critical Power Concept

4.1 Mathematical Models of Critical Power

Gaesser et al. (1995)

The purposes of the study were to: 1) compare parameter estimates of critical power (CP) and anaerobic work capacity (AWC) from five mathematical models. The models included: a two-parameter nonlinear model, a linear P · t model, a linear P model, 3-parameter nonlinear model, and an exponential model (EXP); and 2) examine the correlation between CP and the ventilatory threshold for long-term exercise (LTE T_{vent}). The authors hypothesized that linear and nonlinear regression analysis of the power-endurance relationship for high-intensity exercise would produce significantly different estimates of CP and AWC. The study consisted of 16 physically active males, between 19 and 24 yrs. The subjects performed an incremental exercise test to exhaustion on a cycle ergometer for the determination of peak power. The subjects then completed five to seven constant power output cycle ergometer rides to exhaustion. The power outputs and time to exhaustion data were recorded and used to determine CP and AWC from the five mathematical models. The LTE T_{vent} was determined for 6 subjects during a constant power output ride with the measurement of ventilation and pulmonary gas exchange parameters. The CP and AWC estimates from the five mathematical models differed significantly. The authors found that the three-parameter non-linear model provided the lowest estimate of CP, but the highest estimate of AWC. The exponential model provided the highest estimate of CP. Critical power from the three-parameter non-linear model was not different from the LTE T_{vent}. All other models provided an estimate of CP that was greater than the LTE T_{vent}. The authors concluded that the three-parameter nonlinear model was the preferred model because it provided an estimate of CP closest to the LTE T_{vent}, which provides an estimate of endurance capabilities.

Bull et al. (2000)

The purposes of the study were: 1) to re-examine the findings of Gaesser et al. (1995) by comparing the critical power (CP) estimates from the five mathematical models, and to determine the time to exhaustion (T_{lim}) during cycle ergometry at the lowest CP estimate from the five models. The subjects consisted of nine males (age 25 ± 3 yrs) who were not highly experienced cyclists. All of the subjects completed eight or nine trials on a cycle ergometer with ≥ 24 h separating each trial. The first test subjects performed a maximal incremental test to exhaustion and the power output and heart rate that were attained at exhaustion were considered to be the subject's peak power and peak heart rate. Next the subjects performed five or six randomly ordered trials at power outputs ranging from peak power minus 130 W to peak power plus 50 W, for the estimation of CP. The subjects only performed the sixth trial if they did not have a trial lasting approximately 10 min. Five regression models were used to estimate CP. The models included: the Linear-Total Work (Linear-TW) model, Linear-Power (Linear-P) model, Nonlinear-2 model, Nonlinear-3 model, and Exponential model (EXP). The subjects then performed two continuous rides to exhaustion at lowest estimate of CP from the five mathematical models. The results indicate mean differences among the models used to estimate CP. The Nonlinear-3 model resulted in the lowest mean estimate of CP for each subject. During the two trials at CP, two of the nine subjects did not complete 60 min of cycling.

Housh et al. (2001)

The purpose of the study was to examine the effects of mathematical modeling on critical velocity (CV) estimates and on the oxygen consumption ($\dot{V}O_2$), heart rate (HR), and plasma lactate values that corresponded to the five CV estimates. The subjects consisted of ten males (age 22 ± 2 yrs) who exercise regularly, but were not highly trained. The subjects first performed a continuous incremental treadmill test for the determination of $\dot{V}O_{2max}$. Critical velocity was determined from four randomly ordered treadmill runs to exhaustion with the velocities ranging from 14.5 to 19.3 $km \cdot hr^{-1}$. Five regression models were than used to estimate CV: the Linear Total Distance (TD) model, the Linear-Velocity (V) model, the Nonlinear-2 model, the Nonlinear-3 model, and the exponential model (EXP). The results showed there were significant differences among the mean CV, $\dot{V}O_2$, HR and plasma lactate values for the five models. They also show that the Nonlinear-3 model had a significantly lower mean CV estimate than the other four models and resulted in the lowest estimate of CV for each subject. The EXP model resulted in the highest mean CV estimate compared to the four other models and the highest CV estimate for each subject as well. The $\dot{V}O_2$ and HR values corresponding to the five CV estimates were based on linear regression and, therefore, the significant differences were the same as those for the CV estimates. The plasma lactate values were estimated from power curve analyses and the significant differences did not follow the CV estimates, but they were very similar. The results of the study show that there are significant differences between CV estimates from the five mathematical models.

A. Bull et al. (2008)

The purposes of the study was to: 1) determine if there were differences in critical velocity (CV) estimates from five mathematical models; and 2) examine the time to end of exercise (TTEE), $\dot{V}O_2$, and heart rate (HR) responses during continuous treadmill runs at the five estimates of CV. The subjects consisted of ten adults, six males and four females (mean age, 22 ± 2 year) that were generally active and most ran on a regular basis, but none were elite runners. The subjects completed eight to ten treadmill runs with ≥ 24 h separating each run. The initial visit involved a maximal incremental treadmill test to voluntary exhaustion to determine the maximal oxygen consumption rate ($\dot{V}O_{2max}$). The subjects then performed four or five randomly ordered treadmill runs on separate days for the estimation of CV. The intensity of the runs were set as a percentage of each subject's $\dot{V}O_{2max}$ so that each run lasted between approximately 3 and 20 min. Five mathematical models were than used to estimate CV: the linear, total distance model (Lin-TD); linear velocity model (Lin-V); nonlinear, 2-parameter model (Non-2); nonlinear, three parameter model (Non-3); and an exponential model (EXP). Up to five randomly ordered continuous runs for 60 min (or volitional exhaustion) were then performed by each subject at treadmill velocities that corresponded to the five CV estimates. During the continuous runs at CV, $\dot{V}O_2$ and HR were recorded. Five of the ten subjects completed 60 min at the CV estimate from the Non-3 model and one subject completed 60 min at the CV estimate from the Non-2 model. All runs at CV estimated from the Lin-TD, Lin-V, and EXP models were ended by the subjects prior to 60 min. For the five subjects who did not complete 60 min at any of the CV estimates, the mean TTEE value from the Non-3 model was significantly greater than the other four models. Although the Non-3 model resulted in the lowest estimate of CV for each subject, only 50% of the subjects were able to complete 60 min. These results indicate that CV tends to overestimate the velocity that can be maintained for 60 min.

Bergstrom et al. (2014)

The purpose of the study was to examine the estimates of critical power (CP) and anaerobic work capacity (AWC) from the 2- and 3-paramether models described by Gaesser et al. (1995) and those from the CP_{3min} test described by Burnley et al. (2006) and Vanhatalo et al. (2007). The authors hypothesized: 1) there would be significant differences in the parameter estimates among the 6 models; the three parameter nonlinear (Nonlinear-3) model would produce the lowest estimate of CP and the exponential (EXP) model the highest; 2) the two parameter nonlinear (Nonlinear-2) model would produce the highest estimates of AWC and the linear models the lowest; and 3) estimates of CP and AWC from the CP_{3min} test and the linear models would not be significantly different. The subjects consisted of five women and four men (age 23 ± 3 yrs) all were college-aged and recreationally trained. The subjects completed six exhaustive cycling tests with each test separated by 24-48 hrs. The power output and the time to exhaustion from the four exhaustive rides were fit to the five mathematical models to derive five different estimates of CP and four estimates of AWC. The models consisted of: the Linear-Total Work (Linear-TW) model, Linear-Power (Linear-P) model, Nonlinear-2, Nonlinear-3, and the EXP model. Critical power and AWC were also estimated from the CP_{3min} all-out test. The results indicated that the CP_{3min} test and EXP models were not different and they produced significantly higher estimates of CP than all the other models. The results indicated that CP estimated from the Nonlinear-3 model was 14% lower than those estimated from the EXP model and CP_{3min} test and was 4-6% lower than those from the Linear-TW and Linear-P models. There was no significant difference between the AWC estimates from the Nonlinear-2 and Nonlinear-3 models and they were both greater than the Linear-P, Linear-TW, and CP_{3min}. Therefore, it is shown that the EXP model produced higher estimates of CP, than the other models and the linear models produced the lowest estimates of CP as was hypothesized.

4.2 Number of trials

Burnley et al. (2006)

The purpose to this study was to test three different experimental hypotheses: 1) 3 min of all-out exercise would provide a reproducible power output profile; 2) the test would elicit a peak $\dot{V}O_2$ that would not differ from that measured in a ramp test; 3) the physiological response to prolonged exercise below the power attained in the last 30 s of the all-out test would result in a steady state in $\dot{V}O_2$ and blood lactate, whereas exercise above the end-test power output would result in a continued rise in $\dot{V}O_2$ and blood lactate. The subjects consisted of 11 recreationally active subjects, nine male and two female (age: 27 ± 7 yrs). This study consisted of six laboratory visits, with a minimum of 24 h of recovery between the visits and all tests were completed within 14 days. During the first visit, the subjects performed a ramp protocol for the determination of $\dot{V}O_{2peak}$ and gas exchange threshold (GET). The second visit involved a 3-min bout of all-out cycling, which served as a familiarization test and was not included in the subsequent data analysis. During the next two visits, the subjects performed a 3-min all-out trial. The average power output over the final 30 s of the test was calculated and defined as the end-test power. During the final two visits, the subjects cycled for 30 min or until exhaustion at constant work rates 15 W above or below the end-test power of the 3-min trial in a random order. The peak $\dot{V}O_2$ during the 3-min all-out tests was recorded as the highest $\dot{V}O_2$ measured for 30 s during the test. The authors also determined blood lactate and the highest lactate was recorded as the peak lactate and finally the end-test power was determined as the average power output during the final 30 s of the test. The peak $\dot{V}O_2$ attained in the 3-min tests were similar and they were not significantly different from that measured during the ramp test. The end-test power outputs were not different from each other, were significantly lower than the peak power measured during the ramp test, and significantly higher than the power at the GET. At the constant-work rate trials, 9 of the 11 subjects were able to complete 30 min of exercise, while two were unable to complete 30 min, of the 9 subjects only seven of them met the criterion for a steady-state blood lactate profile. None of the subjects were able to complete 30 min of exercise at 15 W above the end-test power (mean time = 12 min 46 s). The $\dot{V}O_2$ reached at exhaustion was not significantly different from $\dot{V}O_{2peak}$. The study showed that a 3-min all-out cycle ergometer test against a fixed resistance results in a reproducible power output profile and in the attainment of $\dot{V}O_{2peak}$ which is consistent with the first and second hypotheses.

The data suggests that it is possible to establish $\dot{V}O_{2peak}$ during a 3-min all-out exercise test and the test represents a promising method of identifying the maximal steady-state power output in a single test. The results show that exercise above the end-test power is in the severe-intensity exercise domain where $\dot{V}O_2$ and blood lactate increased until exhaustion ensued. The exercise below the end-test power was situated in the heavy-intensity domain where $\dot{V}O_2$ and blood lactate eventually stabilized. The results demonstrate that a 3-min all-out test can be used to estimate a power output at the physiologically important boundary between the heavy- and severe-exercise intensity domains in more than 60% of the subjects. This study therefore suggests that a 3-min bout of all-out exercise represents a promising method of estimating the maximal steady state.

Vanhatalo et al. (2007)

The purpose of the study was to compare the parameters of the power-duration relationship derived from a 3-min all-out cycling test with critical power (CP) and anaerobic work capacity (AWC) derived from the power output and time to exhaustion relationship from a series of five exhaustive exercise bouts. The authors hypothesized that the end-test power (EP) in a 3-min all-out cycling test is equivalent with CP and the work done above the EP (WEP) in the same test is equivalent to the curvature constant parameter (W'). Ten subjects were involved in the study (age 33 ± 9 yrs) and all were accustomed to high-intensity exercise and included competitive road cyclists, club-level distance runners, and those in general fitness training. The subjects completed eight visits with a minimum of 24 h of rest between tests and all testing, was completed within

3 weeks. The subjects performed an incremental ramp protocol for the assessment of $\dot{V}O_{2peak}$ and gas exchange threshold (GET). The second visit was a familiarization session for the 3-min all-out test. On the following visits, the subjects performed a 3-min all-out test to determine EP and WEP and five predicting trials at constant work rates to exhaustion to determine CP and W'. The results indicated the peak $\dot{V}O_2$ measured in the 3-min all-out test was significantly lower than the ramp-test $\dot{V}O_{2peak}$. When the authors looked at the power output data reduced to 15-s averages and compared them they found a significant decrease from one time bin to the next with the exception of the final 45 s. When the authors looked at the CP estimates derived using the two models, work- time model and 1/time model, they were correlated well and were not significantly different from the all-out test EP or the two W' estimates from the WEP. The authors used the work-time model for further analysis because generally it fit the data better. The predictions that were based on the 3-min test parameters tended to underestimate the actual times to exhaustion. The predicted and actual times to exhaustion measured in the four predicting trials were however not significantly different. The results support the first hypothesis in showing that the power output in a 3-min all-out cycling test fell to a relatively steady level that was almost identical to CP. WEP was not significantly different and was highly correlated with W' which was consistent with the second hypothesis. The study demonstrated that the EP in a 3-min all-out cycling test was not significantly different to CP and WEP in the same test was found to be similar to, but slightly lower than W'.

Bergstrom et al. (2012)

The purpose of the study was to develop a 3-minute, all-out test protocol using the Monark cycle ergometer for estimating critical power (CP) and anaerobic work capacity (AWC) with the resistance based on body weight. The authors hypothesized that a 3-minute, all-out test on a Monark cycle ergometer, with the resistance set at 3.5 or 4.5% of the subject's body weight, would provide accurate estimates of CP and AWC when compared with those from the CP_{PT} and CP_{3min} tests. The subjects for the study consisted of six males and six females (age: 23.2 ± 3.5 yrs) that were moderately trained, but not competitive cyclists. Each subject performed an incremental test to exhaustion, a critical power test, 3-minute all-out test, and Monark 3-minute all-out tests. The incremental test was used to determine $\dot{V}O_{2peak}$ and gas exchange threshold (GET). Critical power and AWC were calculated from the total work versus time to exhaustion relationship from a series of four constant power output rides (CP_{PT}). In addition, estimates of CP and AWC were calculated as the average power output over the last 30 s of the test and the integral above the asymptote of the power-time relationship, respectively, for the CP_{3min}, $CP_{3.5\%}$, and $CP_{4.5\%}$ tests. The results indicate no significant differences among estimates of CP from the CP_{PT}, $CP_{3.5\%}$, and $CP_{4.5\%}$ tests. The mean CP from the CP_{3min} test, however, was greater than those from the CP_{PT} and $CP_{3.5\%}$ tests, but it was not different from the $CP_{4.5\%}$ test. The CP values from the CP_{PT}, CP_{3min}, and $CP_{4.5\%}$ were highly intercorrelated. No significant mean differences were seen among AWC values for CP_{PT}, CP_{3min}, and $CP_{4.5\%}$ tests; however AWC values from the CP_{PT} and CP_{3min} tests were significantly greater than from the $CP_{3.5\%}$ test. The AWC values from the 4 tests were highly intercorrelated. The findings indicate CP and AWC could be estimated from a 3-minute all-out test with the resistance set at 4.5% of the subject's body weight. The study indicated CP and AWC could be accurately estimated from the $CP_{4.5\%}$ test but not the $CP_{3.5\%}$ test.

Summary:

Previous studies (Bergstrom et al. 2014, Bull et al. 2000, Bull et al. 2008, Gaesser et al. 1995, Housh et al. 2001) have examined the effects of linear and nonlinear mathematical models on estimates of critical power (CP) and anaerobic work capacity (AWC). For example, studies (Gaesser et al. 1995, Bull et al. 2000, Housh et al. 2001, Bergstrom et al. 2014) reported significant differences among CP and AWC estimates derived from five different models: the Linear-Total Distance (Linear-TD) model, the Linear-Velocity (Linear-V) model, the two-parameter non-linear (Nonlinear-2) model, the three-parameter non-linear (Nonlinear-3) model, and the exponential (EXP) model. The Nonlinear-3 model provided the lowest estimate of CP, but the highest estimate of AWC and the EXP model provided the highest estimate of CP. Housh et al. (2001) examined the effect of mathematical modeling on critical velocity (CV), the treadmill analog to CP. The treadmill analog of CP is determined from the total distance and time to exhaustion of multiple constant velocity runs. The authors (Bull et al. 2000 and Housh et al. 2001) findings were consistent with Gaesser et al. (1995) and indicated that the Nonlinear-3 model produced a significantly lower CV estimate than the other models (Linear-TD model, Linear-V model, Nonlinear-2 model, and EXP model). In addition, Bull et al. (2008) examined the times to exhaustion during treadmill running at CV derived from five mathematical models (Linear-TD model, Linear-V model, Nonlinear-2 model, Nonlinear-3 model, and an EXP model) and suggested that the Nonlinear-3 model was the best for predicting CV estimates, but that CV tended to overestimate the velocity that can be maintained for 60 min. Thus, the results of previous studies (Bergstrom et al. 2014, Bull et al. 2000, Bull et al. 2008, Gaesser et al. 1995, Housh et al. 2001) indicate that there are significant differences among CP and CV estimates from the five mathematical models (Linear-TD model, Linear-V model, Nonlinear-2 model, Nonlinear-3 model, and an EXP model).

The critical power (CP) test is physically demanding, requiring multiple, exhaustive work bouts. To improve the applicability of the test, previous research has examined the number of trials necessary to accurately estimate CP. Burnley et al. (2006) developed a 3-min all-out test to in an attempt to identify the maximal power output where steady state responses can be achieved. The authors (Burnley et al. 2006) reported that power output plateaued during the final 30 seconds of the test. The average power output over the final 30 s of the test was defined as the end-test power, and hypothesized to represent the maximal power output where metabolic parameters would reach a plateau. The authors (Burnley et al. 2006) reported that none of the subjects were able to maintain 30 min of exercise above the end-test power and $\dot{V}O_2$ and blood lactate increased until exhaustion. During exercise below the end-test power $\dot{V}O_2$ and blood lactate eventually stabilized, and 9 out of the 11 subjects were able to complete 30 min of exercise. Thus, the authors suggested that the end-test power provided a demarcation of heavy from severe exercise intensities and the 3-min bout of all-out exercise represented a promising method of estimating the maximal steady state. Vanhatalo et al. (2007) further examined the 3-min all-out test to compare the end-test power output to critical power. The authors (Vanhatalo et al. 2007) compared the parameters of the power-duration relationship derived from a 3-min all-out cycling test with those derived from the linear relationship between total work and time to exhaustion from a series of five different constant power output rides. Vanhatalo et al. (2007) demonstrated that the end-power in a 3-min all-out cycling test was not significantly different from CP and the work done above the end power (WEP; the integral of the power output versus time relationship above end-test power) was found to be similar to, but slightly lower than the curvature constant parameter (AWC). The authors (Vanhatalo et al. 2007) suggested that the 3-min all-out test could provide estimates of both CP and AWC. Although, the 3-min all-out test reduced the number of work bouts necessary to estimate CP and AWC, it required an additional graded exercise test and measurement of gas exchange parameters prior to testing. Thus it was not truly a single work bout test. Thus, Bergstrom et al. (2012) attempted to further simplify the protocol for the 3-min all-out test using the cycle ergometer with the resistance based on body weight to provide a more practical way to estimate CP and AWC. The authors (Bergstrom et al. 2012) reported that CP and AWC, estimated from a 3-min all-out test with the resistance set at 4.5% of body weight, were not different than the estimates derived from the multiple work bout model. These findings (Bergstrom et al. 2012) indicate that CP and AWC could be estimated from a single, 3-min all-out test with the resistance set at 4.5% of the subject's body weight.

Chapter III: Methods

Experimental Design

The subjects completed a total of seven visits with a minimum of 24 hours between each visit. During the first visit, the subjects performed a graded treadmill test to exhaustion to determine maximal oxygen uptake ($\dot{V}O_{2peak}$) and the velocity associated with $\dot{V}O_{2peak}$ ($v\dot{V}O_{2peak}$). The subjects were asked to estimate their maximal-effort times to complete (ET_{com}) four different distances (400m, 800m, 1600m, and 3200m). The ET_{com} was used to derive the CV and ARC from the linear-total distance versus T_{lim} model. During the remaining six visits, the subjects performed maximal-effort runs at distances of 200m, 600m, and 1000m. Each distance was performed twice, in a randomized order, and the actual time to complete (AT_{com}) the run was recorded. The predicted time to complete (PT_{com}) three distances (200, 600, and 1000m) was derived using the CV and ARC estimates from the TD versus ET_{com} relationship. The PT_{com} and AT_{com} for the maximal-efforts runs were used to access the validity of the equation: $PT_{com} = ARC / (V – CV)$ for predicting performance, utilizing the CV parameters derived from the predicted times. In addition, the reliability of the performance at each distance (200, 600, and 1000m) was determined.

Subjects

A convenience sample of twelve (6 males, 6 females, age: 23.5 ± 3.6 years, height: 174.1 ± 8.0 cm, weight: 66.7 ± 9.0 kg) trained runners with experience in running distances, between 15 to 45 miles per week were recruited for this study. The study was approved by the University of Kentucky Institutional Review Board for Human Subjects. All subjects completed a medical history questionnaire and signed a written informed consent document prior to testing. Twelve runners completed the incremental treadmill test and provided estimates of their ET_{com} for four distances (400m, 800m, 1600m, and 3200m). Two subjects, however, were removed from the analyses because they provided estimates of ET_{com} that resulted in negative ARC values derived from the total distance versus ET_{com} relationship. Therefore, the analyses included 10 subjects (5 males, 5 females, age: 22.6 ± 3.2 years, height: 173.7 ± 8.7 cm, weight: 64.2 ± 7.4 kg).

Body Composition Assessments

Body composition assessments were completed with Bioelectrical Impendence Analysis (BIA; Bodystat QuadScan 4000, Douglas, UK) prior to the exercise testing during visit 1. The BIA device was calibrated before measurements were taken and subjects were instructed to lay in a supine position on a non-conductive surface. The impendence at all frequencies provided (5, 50, 100 & 200 kHz), percent body fat, and total body water was recorded for each subject utilizing the device's prediction equation.

Determination of peak values

During visit 1, the subjects completed a graded treadmill test to exhaustion for the determination of $\dot{V}O_{2peak}$ and velocity at $\dot{V}O_{2peak}$ ($v\dot{V}O_{2peak}$). Prior to the test, each subject completed a 3 min warm-up on the treadmill at a velocity of 4.8 $km \cdot h^{-1}$ and 0% grade, followed by a 3 min passive recovery. Following the warm-up, each subject was fitted with a nose clip and had to breathe through a 2-way valve (Hans Rudolph 2700 breathing valve, Kansas City, MO, USA). Expired gas samples were collected and analyzed using a calibrated TrueMax 2400 metabolic cart (Parvo Medics, Sandy, UT, USA). The gas analyzers were calibrated with room air and gases of known concentrations (16% O_2 and 4% CO_2) prior to all testing sessions. The O_2, CO_2, and ventilatory parameters were recorded breath-by-breath and expressed as 20 s averages (Robergs 2010). In addition, HR was recorded with a Polar Heart Rate Monitor (Polar Electro Inc., Lake Success, NY) that was synchronized with the metabolic cart. Heart rate was recorded continuously throughout the test and expressed as 20 s averages. Each subject gave a rating of perceived exertion (RPE) during the last 10 s of each minute using the Borg 6-20 RPE scale (Borg 1970). The incremental test began at a treadmill velocity of 6.4 $km \cdot h^{-1}$ and 0% grade. The treadmill velocity increased by 1.6 $km \cdot h^{-1}$ every 2 minutes until the treadmill velocity reached 14.4 $km \cdot h^{-1}$. Following the 14.4 $km \cdot h^{-1}$ stage, the velocity no longer was increased, however, the treadmill grade was increased by 2% every 2 min until the subject no longer could maintain the running velocity and grasped the handrails to signal exhaustion. The $\dot{V}O_{2peak}$ was defined as the highest 20 s average $\dot{V}O_2$ value recorded during the test. The velocities performed at 0% grade (6.4 to 14.4 $km \cdot h^{-1}$), were plotted against $\dot{V}O_2$ and the regression equation derived was used to determine the $v\dot{V}O_{2peak}$.

Estimated Performance Times and CV Parameter Determination

Following the graded treadmill test, each subject completed a written survey asking them to provide the ET_{com} for maximal-effort runs at 400m, 800m, 1600m, and 3200m. The TD was plotted against ET_{com} for each of the four distances. The CV and ARC were defined as the slope and y-intercept of the regression line, respectively, of the TD versus ET_{com} relationship (Figure 1).

Determination of PT_{com}

The PT_{com} for three distances (200, 600, and 1000m) was derived using the CV and ARC estimates from the TD versus ET_{com} relationship, along with the average running velocities (V) calculated for each distance from the AT_{com} ($V = TD / AT_{com}$). The PT_{com} values were derived for each of the standard distances using the equation: $PT_{com} = ARC / (V – CV)$.

Examination of the Estimated CV and ARC Parameters

During visits 2 – 7, the PT_{com} values for the 200m, 600m, and 1000m distances, obtained from the TD versus ET_{com} relationship, were validated against the AT_{com} runs at 200m, 600m, and 1000m. All of the runs were conducted outside on various sidewalks using a survey wheel on a relatively flat surface. The subjects performed a standardized running warm-up. Following the warm-up, a rest period of 10 min was given prior to beginning the max-effort run. Maximal-effort runs at each of the three distances were performed on separate days, and each distance was performed twice, in a randomized order with a minimum of 24 h of recovery between runs. The AT_{com} was recorded by the tester using a stopwatch. The subjects were given strong verbal encouragement during each run and were not aware of how much time had elapsed. The faster of the two trials at each distance was used to compare to the PT_{com} derived from the CV model.

Statistical Analysis

The mean differences between the PT_{com} determined from the TD versus ET_{com} relationship and the fastest recorded AT_{com} for each distance were analyzed using paired samples t-tests. The relationship between the PT_{com} and AT_{com} were assessed using Pearson correlations, coefficients of determination, and the standard error of the estimates (SEE). The relative reliability of AT_{com} for each distance, were examined using the intraclass correlation coefficients (ICC), with the inclusion of systematic error 2,1 and 2,k equations (Weir 2005). Absolute reliability of AT_{com} for each distance was examined using the standard error of the measurement (SEM). Bland-Altman plots were used to assess the agreement between: 1) PT_{com} and AT_{com} at each distance (200, 600, and 1000m); and 2) the first and second set of performance trials for each distance (200, 600, and 1000m). Mean differences were assessed with a t-test about a single mean, the 95% limits of agreement were calculated (±1.96 SD), and the relationship between mean scores and actual times were assessed with the regression analyses. An alpha level of $p \leq 0.05$ was considered statistically significant for all analyses.

Chapter IV: Analysis of Data

Results

The mean ± SD and range of values derived from the incremental treadmill test and body composition analyses are presented in Table 1. The ET_{com} for the four distances (400m, 800m, 1600m, and 3200m) used to determine the CV and ARC ranged from 60 s to 1080 s. The r^2 values for the TD versus ET_{com} relationship ranged from 0.996 to 1.000. The mean (± SD) CV and ARC were 14.3 ± 2.9 $km \cdot h^{-1}$ (81.3% of $v\dot{V}O_{2peak}$) and 125.07 ± 32.43 m, respectively.

The mean ± SD and range of values for the PT_{com} and AT_{com} for the 200, 600, and 1000m runs are presented in Table 2. The results of the paired samples t-test, where $p \leq 0.05$ signifies a significant difference, indicated the predicted values (PT_{com} 53.77 ± 9.28 s) were significantly greater than actual values (AT_{com} 32.40 ± 4.55 s), ($t_{(9)} = 6.90$, p = <0.01), and there was no significant relationship ($r^2 = 0.02$, SEE = 4.79 s, p = 0.72) between the PT_{com} (53.77 ± 9.28 s) and AT_{com} (32.40 ± 4.55 s) at 200m (Figure 2). The results of the Bland-Altman analyses are presented in Figure 3. The 95% limits of agreement (LOA) for the AT_{com} versus PT_{com} estimates ranged from -31.16 to -11.58 s.

The results of the paired samples t-test indicated there was no significant difference ($t_{(9)} = -1.10$, p = 0.30) and no significant relationship ($r^2 = 0.04$, SEE = 21.18 s, p = 0.59) between the PT_{com} (111.16 ± 19.14 s) and AT_{com} (119.90 ± 20.35 s) at 600m (Figure 4). The results of the Bland-Altman analyses are presented in Figure 5. The 95% LOA for the AT_{com} versus PT_{com} estimates ranged from -16.36 to 33.84 s.

The results of the paired samples t-test indicated there was no significant difference ($t_{(9)} = -0.34$, p = 0.74) and no significant relationship ($r^2 = 0.05$, SEE = 33.47 s, p = 0.53) between the PT_{com} (198.52 ± 127.44 s) and AT_{com} (213.30 ± 32.40 s) at 1000m (Figure 6). The results of the Bland-Altman analyses are presented in Figure 7. The 95% LOA for the AT_{com} versus PT_{com} estimates ranged from -123.67 to 153.23 s.

The test-retest reliability at each distance (200, 600, and 1000m) resulted in ICC values of 0.98 to 0.99. The SEM values for 200, 600, and 1000m runs were 0.12 s, 0.87 s, and 0.69 s, respectively. The results of the Bland-Altman analyses for trial 1 and trial 2 for all three distances are presented in Figures 8, 9, and 10. The 95% LOA for trial 1 versus trial 2 estimates ranged from -1.57 to 0.37 s for the 200m, -6.55 to 5.75 s for the 600m, and -7.02 to 6.82 s for the 1000m.

Discussion

One purpose of the present study was to determine if estimated performance times at four different distances can be used to accurately define the parameters of the CV test. The TD was plotted as a function of the ET_{com} for four running distances (400, 800, 1600, and 3200m) (Figure 1). The r^2 values for the TD versus T_{lim} (0.996 – 1.000) relationship were consistent with the r^2 values (0.987 – 0.999) reported in previous studies of recreationally trained subjects (Pepper et al. 1992), and indicated a close relationship between running distance and time. These findings suggested that the mathematical model used to derive the CV parameters (CV and ARC) from times to exhaustion during constant velocity running, was also applicable to estimated performance times at specified distances.

The mean and range of CV (14.3 ± 2.9 $km \cdot h^{-1}$; 10.2 – 17.9 $km \cdot h^{-1}$) and ARC (0.13 ± 0.032 km; 0.09 – 0.11 km) values in the present study were higher and lower, respectively, than the mean and range of CV (13.43 ± 2.04 to 13.7 ± 1.1 $km \cdot h^{-1}$; 10.43 –

17.85 $km \cdot h^{-1}$) and ARC (0.20 ± 0.063 km; 0.11 – 0.23 km) values previously reported for recreationally trained subjects (Pepper et al. 1992 and Housh et al. 2001). These differences in CV and ARC values may be related to the training status of the subjects. Specifically, the subjects in the present study, although not elite, were experienced runners and had a greater aerobic capacity (63.96 ± 12.39 $ml \cdot kg^{-1} \cdot min^{-1}$ [Table 1]), than previous samples of subjects who exercised regularly, but were not highly trained in running (48.6 ± 7.1 to 54.4 ± 6.6 $ml \cdot kg^{-1} \cdot min^{-1}$). Thus, the ARC and CV values in this present study were slightly lower and higher, respectively, compared with previous studies examining recreationally trained subjects (Pepper et al. 1992 and Housh et al. 2001). These differences may be related to the slightly greater aerobic capacity and the mode specific training adaptations of the current sample of experienced runners, compared with generally active individuals previously reported (Pepper et al. 1992 and Housh et al. 2001).

One unique application of the CV model is the ability to predict the time to exhaustion (PT_{com}) at any velocity greater than CV using the equation: PT_{com} = ARC / (V – CV) (Moritani et al. 1981). A second purpose of this study was to determine if the parameters of the CV test could be used to estimate PT_{com} of distances performed at velocities greater than CV using the equation PT_{com} = ARC / (V – CV). In the present study, the accuracy of the PT_{com} estimated from the CV and ARC parameters derived from the TD versus ET_{com} relationship was examined for three distances (200, 600, and 1000m). At 200m (~150% of CV) the PT_{com} overestimated the AT_{com}, whereas the PT_{com} for the 600m (125% of CV) and 1000m (118% of CV) were not significantly different from the AT_{com} (Table 2). There were, however, no significant relationships between the AT_{com} and PT_{com} for any of the distances (Figures 2, 4, and 6), which indicated a lack of agreement between AT_{com} and PT_{com} and suggested significant individual variability in the prediction. Currently, there are conflicting data regarding the accuracy of performance prediction for intensities above CV or CP (Pepper et al. 1992 and Housh et al. 1989). For example, Pepper et al. (1992) reported no significant differences and significant relationships between the predicted and actual times to exhaustion at 85% and 115% of CV, however, the time to exhaustion was over predicted at 100% and under predicted at 130% of CV. In addition, during cycle ergometry, there were no differences and significant relationships ($r = 0.84 – 0.89$, $p < 0.05$) between the predicted and actual times at power loadings above CP (Housh et al. 1989). At CP, however, the actual time to exhaustion was significantly less than the predicted time (Housh et al. 1989). The discrepancy between actual and predicted times for intensities greater than 130% of CV in the present study, as well as previous studies (Pepper et al. 1992), may be related to the limitations of the mathematical model. Typically, the CV model is determined from work bouts ranging from 1 to 20 min (Bull et al. 2008, Poole et al. 1988) and in the present study the range of times used to determine CV and ARC was 1 to 18 min. The prediction of the 200m time required extrapolation outside the range of values used to determine the parameters of the CV test. Thus, the significant difference between the PT_{com} and AT_{com} at higher intensities (>130% of CV) may be related to the limitations of the mathematical model to predict performance outside the range of values used for the CV and ARC parameter estimations.

The non-significant differences between PT_{com} and AT_{com} at 600m and 1000m (Table 2), reflecting 125% and 118% of CV, respectively, in the present study was consistent with previous data indicating no significant differences between actual and estimated times at 115% of CV (Pepper et al. 1992). The lack of relationship between PT_{com} and AT_{com} (Figures 2, 4, and 6), however, was not consistent with previous research (Housh et al. 1989, Pepper et al. 1992). The lack of relationship between PT_{com} and AT_{com} indicated significant individual variability in the performance predictions. The individual variability in performance prediction maybe related to the inclusion of subjects who were not experienced at performing time trials at shorter distances such as the 400m and 800m used to derive the parameters for the PT_{com} estimates. In addition, the SEE values for the three runs indicated a possible error in prediction of 4.8 s for a 32.4 s run (14.8% of mean), 21.2 s for a 120 s run (17.7% of mean), and 33.5 s for a 213s (15.7% of mean) run (Figures 2, 4, and 6). These SEE values indicated an error that was too large to be of practical value when predicting performance at these distances. Thus, the current findings, in conjunction with those of others (Housh et al. 1989, Pepper et al. 1992), indicated that the prediction of performances utilizing the CP and CV models tend to under or overestimate the actual times to exhaustion for high intensity, shorter duration trials (>130% of CV), and resulted in SEE values for all three distances that were too great to provide accurate estimates of performance. Therefore, the current findings did not support the validity of the equation $PT_{com} = ARC / (V – CV)$.

Limitations and Future Directions

This study examined the accuracy of estimated performance times to define the parameters of the CV model. There were several limitations, however, to this study. Specifically, this study required subjects to complete the validation runs on sidewalks. This resulted in an uncontrolled environment and various weather conditions between and within the subjects for each of the three running trials. It is possible that these conditions resulted in slower or faster times depending on the type of condition. Future studies should examine running performance times to validate the CV test parameters derived from estimated running performance in a controlled environment to limit any influence of the environment between and within each subject.

Another limitation of this study was that the CV and ARC parameters derived from ET_{com} could not be compared to the CV and ARC parameters derived from AT_{com}. The times to complete the running distances (200, 600, and 1000m) used in this study were too short (less than 1 min for the 200m) and did not result in a range of times that was great enough (typically 1 – 10 min is recommended) (Housh et al. 1989) to estimate the CV and ARC parameters derived from the TD versus actual performance time relationship. Future studies should compare the CV and ARC parameters derived from the TD versus ET_{com} and TD versus AT_{com} relationships using longer distances that result in a longer time to completion.

Conclusions

In conclusion, the purposes of this study were to determine: 1) if estimated performance times at four different distances could be used to accurately define the parameters of the CV test (CV and ARC); and 2) if those parameters can be used to estimate PT_{com} of distances performed at velocities greater than CV using the equation $PT_{com} = ARC / (V - CV)$. The TD versus ET_{com} relationship was highly linear ($r^2 = 0.996 - 1.000$) and indicated a close relationship between running distance and time. These findings suggested that the mathematical model used to derive the CV parameters (CV and ARC) from times to exhaustion during constant velocity running, was also applicable to estimate performance times at specified distances. The comparisons of the PT_{com} versus the AT_{com} indicated the PT_{com} overestimated the AT_{com} for the 200m. There were no significant differences between the PT_{com} and AT_{com} for the 600 and 1000m, however, there were no significant relationships between PT_{com} and AT_{com} at any of the distances. These findings were consistent with other studies that also found a discrepancy between actual and predicted times utilizing the CP and CV model (Pepper et al. 1992 and Housh et al. 1989). In addition, the SEE values for all three distances indicated error in prediction that was too great to be of practical values for the 200m, 600m, and 1000m distances. Therefore, the principal findings of this study were that the CV model could be applied to estimated performance times during outdoor running to derive the CV and ARC parameters, but the parameters of the test could not be used to accurately estimate performance times above CV using the equation $PT_{com} = ARC / (V – CV)$.

Table 1. Mean ± SD for subject demographics (N = 10).

Variables	Mean ± SD
Age (yrs)	22.6 ± 3.24
Height (cm)	173.72 ± 8.66
Weight (kg)	64.23 ± 7.36
Body Comp (% Fat)	14.16 ± 9.16
Body Comp (Total Body Water lt)	39.01 ± 6.60
$\dot{V}O_{2max}$ ($L \cdot min^{-1}$)	4.12 ± 1.02
$\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	63.96 ± 12.39

Table 2. Mean ± SD for predicted time to completion (PT_{com}) and actual time to completion (AT_{com}) for the 200, 600, and 1000m runs.

Distance	PT_{com} (seconds)	AT_{com} (seconds)
200 m	53.77 ± 9.28*	32.40 ± 4.55
600 m	111.16 ± 19.14	119.90 ± 20.35
1000 m	198.52 ± 127.44	213.30 ± 32.40

*significantly greater than actual time at $p \leq 0.05$

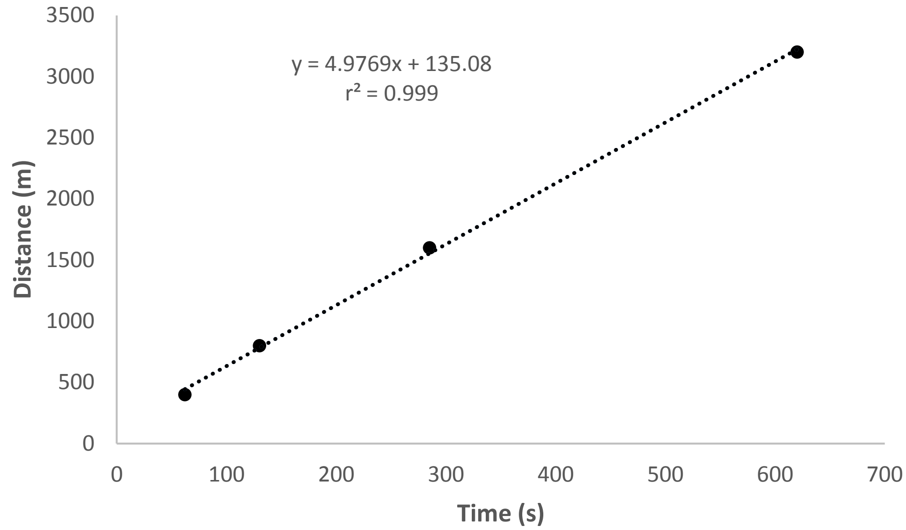

Figure 1. Example of the total distance (TD) versus estimated time to completion (ET_{com}) relationship for one representative subject.

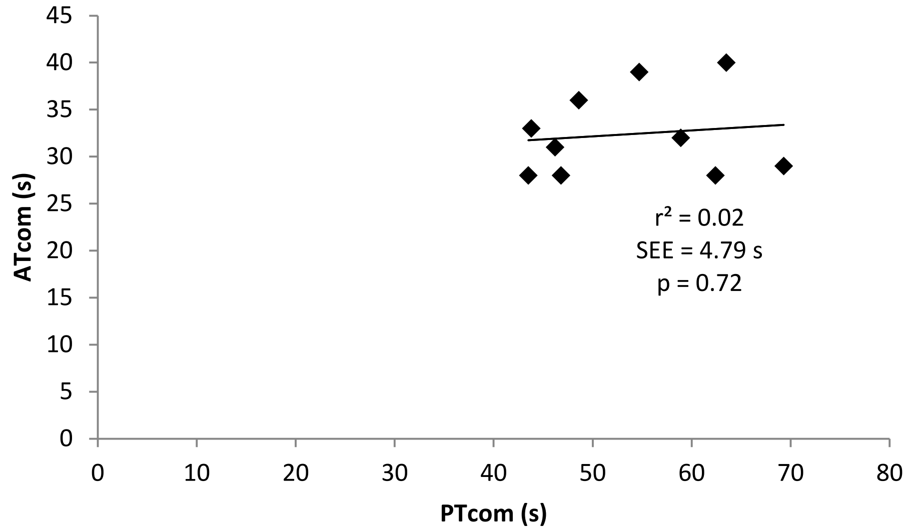

Figure 2. The relationship between the actual times to completion (AT_{com}) versus the predicted times to completion (PT_{com}) for the 200m in 10 male and female subjects.

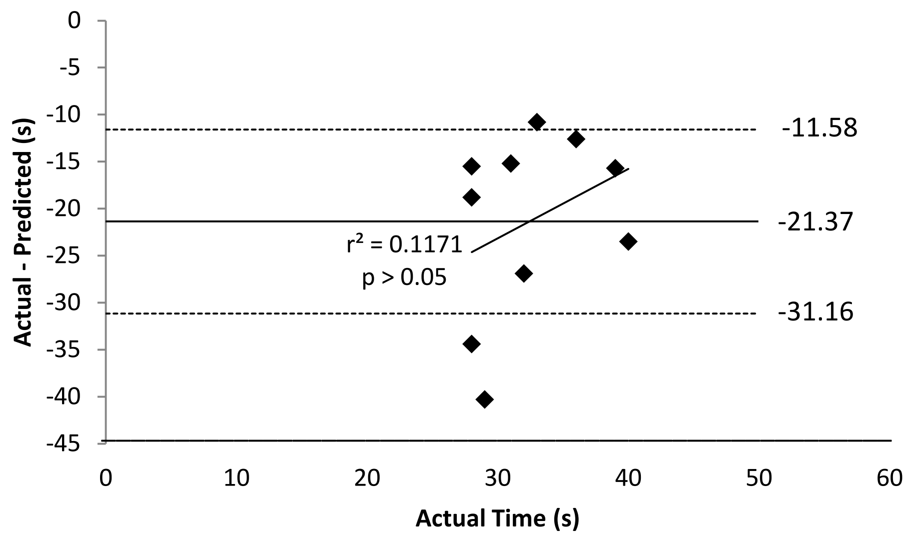

Figure 3. Modified Bland Altman analysis of agreement between the actual minus predicted and actual time for the 200m run in 10 male and female subjects. The middle solid line represents the mean of the difference of the actual time and predicted time. The upper and lower dotted lines represent the bias ±1.96 SD (95% Limits of Agreement).

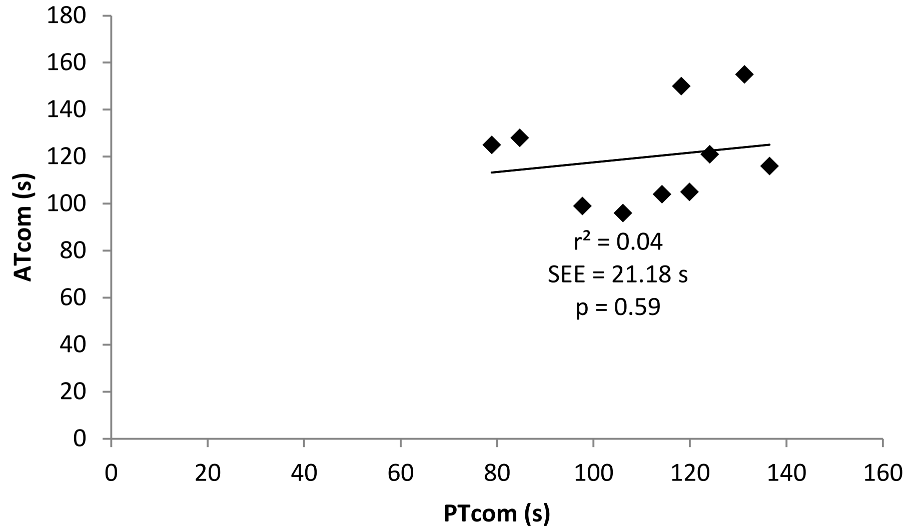

Figure 4. The relationship between the actual times to completion (AT_{com}) versus the predicted times to completion (PT_{com}) for the 600m run in 10 males and females.

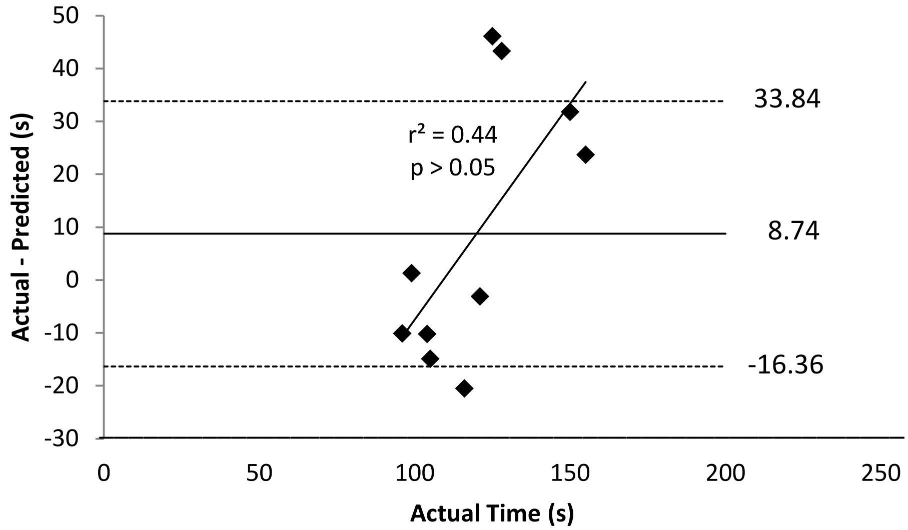

Figure 5. Modified Bland Altman analysis of agreement between the actual minus predicted and actual time for the 600m run in 10 male and female subjects. The middle solid line represents the mean of the difference of the actual time and predicted time. The upper and lower dotted lines represent the bias ±1.96 SD (95% Limits of Agreement).

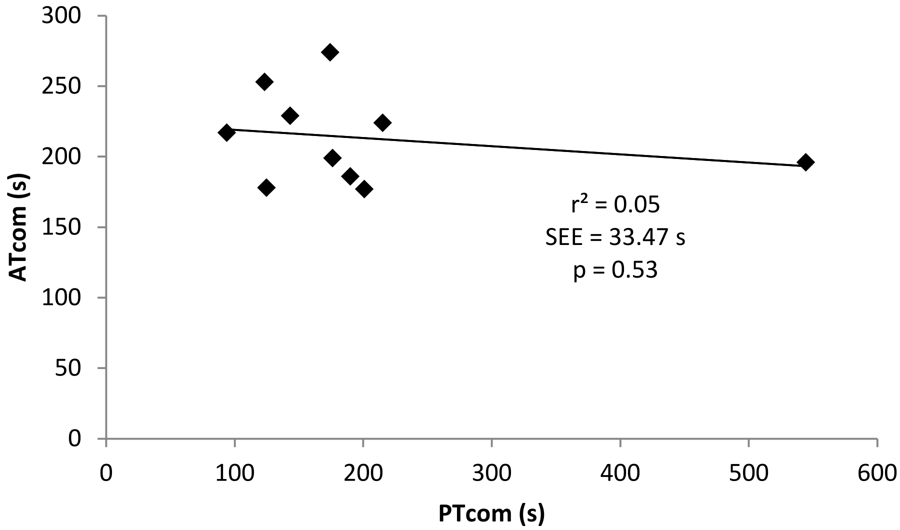

Figure 6. The relationship between the actual times to completion (AT_{com}) versus the predicted times to completion (PT_{com}) for the 1000m run in 10 male and female subjects.

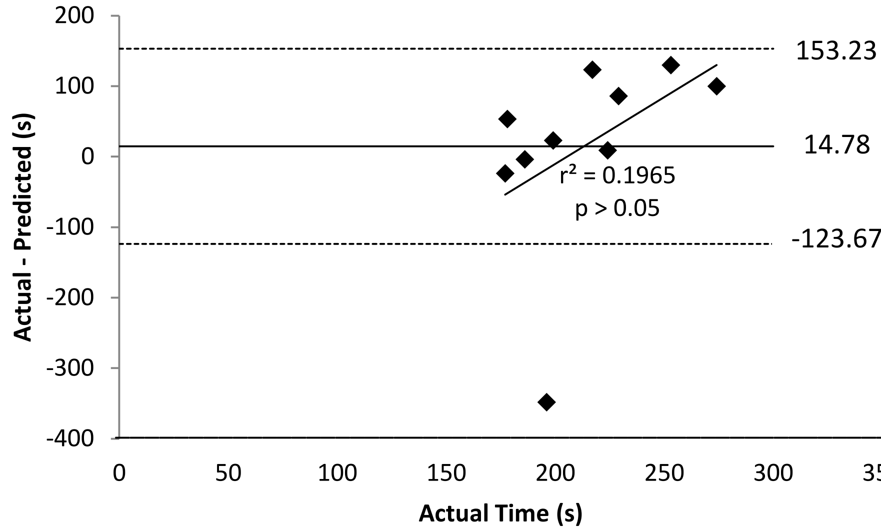

Figure 7. Bland Altman analysis of agreement between the actual minus predicted and actual time for the 1000m run in 10 male and female subjects. The middle solid line represents the mean of the difference of the actual time and predicted time. The upper and lower dotted lines represent the bias ±1.96 SD (95% Limits of Agreement).

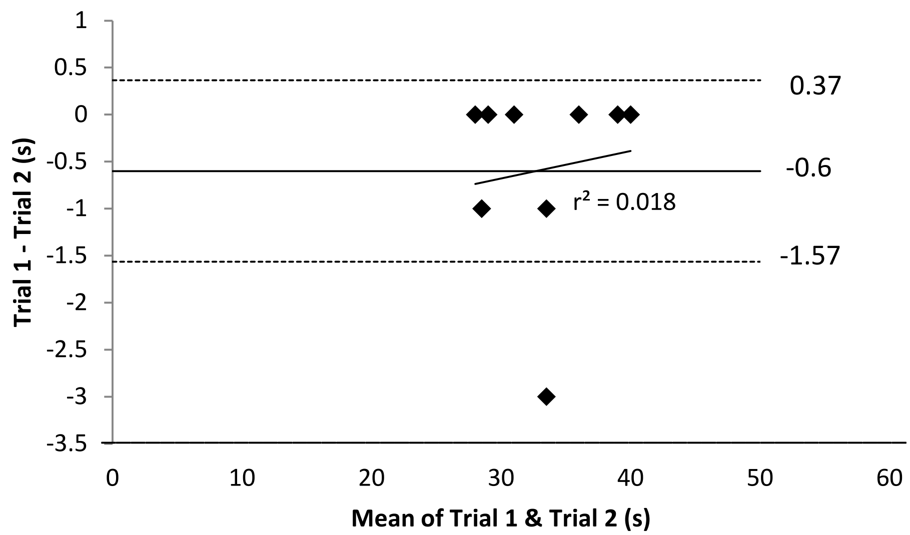

Figure 8. Bland Altman analysis of agreement between trial 1 and trial 2 for the 200m run in 10 male and female subjects. The middle solid line represents the mean of the difference of trial 1 and trial 2. The upper and lower dotted lines represent the bias ±1.96 SD (95% Limits of Agreement).

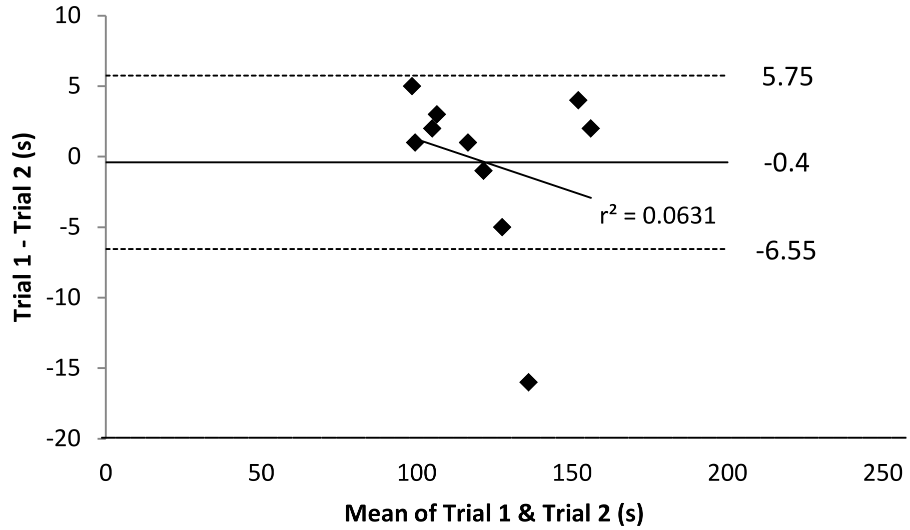

Figure 9. Bland Altman analysis of agreement between trial 1 and trial 2 for the 600m run in 10 male and female subjects. The middle solid line represents the mean of the difference of trial 1 and trial 2. The upper and lower dotted lines represent the bias ±1.96 SD (95% Limits of Agreement).

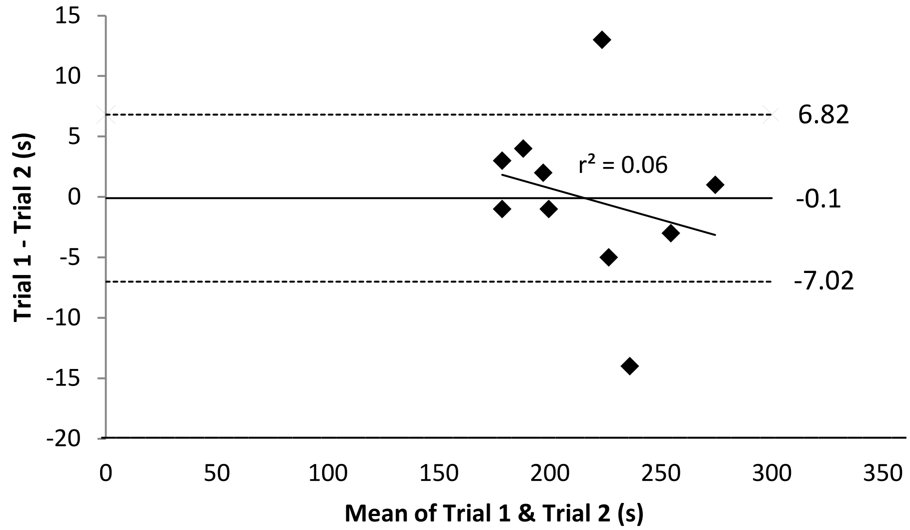

Figure 10. Bland Altman analysis of agreement between trial 1 and trial 2 for the 1000m run in 10 male and female subjects. The middle solid line represents the mean of the difference of trial 1 and trial 2. The upper and lower dotted lines represent the bias ±1.96 SD (95% Limits of Agreement).

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