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EXAMINATION OF RESISTANCE SETTINGS BASED ON BODY WEIGHT FOR
THE 3-MINUTE ALL-OUT CRITICAL POWER TEST

THESIS

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

By

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Lexington, Kentucky

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2016

ABSTRACT OF THESIS

EXAMINATION OF RESISTANCE SETTINGS BASED ON BODY WEIGHT FOR THE 3-MINUTE ALL-OUT CRITICAL POWER TEST

This study examined whether the critical power (CP) and anaerobic work capacity (AWC) estimates from the CP 3-min all-out ($CP_{3\text{min}}$) test were affected by the percentage of body weight used to set the resistance on a Monark cycle ergometer. Twenty-one subjects (11 women and 10 men) were placed into one of three groups ($n=7$) based on activity level; recreationally trained (REC), aerobic and anaerobic sport (SPORT), and endurance trained (END). The $CP_{3\text{min}}$ test was conducted at 4.5% of body weight ($CP_{4.5\%}$) and at a resistance setting based on group activity level (CP_{ACT} ; REC = 3%, SPORT = 4%, and END = 5% of body weight). There were no differences between the $CP_{4.5\%}$ or CP_{ACT} estimates in any of the three training groups. The $AWC_{3\%}$ estimates were significantly lower than the $AWC_{4.5\%}$ for the REC group, but there were no differences in the $AWC_{4.5\%}$ and AWC_{ACT} for the SPORT or END groups. The principal finding of this study was that a resistance of 4.5% of body weight for $CP_{3\text{-min}}$ test may be used to estimate CP and AWC, without regard to the training status of the subjects.

Marlene Janice Schulte

May 27, 2016

EXAMINATION OF RESISTANCE SETTINGS BASED ON BODY WEIGHT FOR
THE 3-MINUTE ALL-OUT CRITICAL POWER TEST

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Chapter 1: Introduction

The critical power (CP) concept was developed by Monod & Scherrer (20) for a single muscle or muscle group and defined as the maximum work rate a muscle can maintain for a very long duration without fatigue. The CP test requires the measurement of the amount of work (W_{lim}) completed during a series of exhaustive, muscular work tests at various, constant power outputs and the time to exhaustion (T_{lim}) (20). Monod & Scherrer (20) reported a linear relationship between W_{lim} and the T_{lim} , defined by the regression equation; $W_{lim} = a + b \cdot T_{lim}$. The slope, factor “b”, represented the CP, while the y-intercept, factor “a”, represented an energetic reserve known as anaerobic work capacity (AWC). Based on these findings, the authors suggested the maximum amount of dynamic work a muscle can do in a given time can be determined. Moritani et al. (21) expanded the findings of Monod & Scherrer (20), to relate the CP concept to whole-body exercise. The relationship between W_{lim} and T_{lim} for cycle ergometry was highly linear supporting the hypothesis that CP concept was applicable to whole-body exercise (21).

One of the primary applications the CP parameter is the demarcation of the exercise intensity domains (3, 14). Gaesser & Poole (14) described three distinct exercise intensity domains; moderate, heavy, and severe. The moderate domain includes exercise intensities that result in $\dot{V}O_2$ and blood lactate response that reach steady state values within 2-3 min and exercise can be maintained for at least 60 min (3, 14). The gas exchange threshold (GET) demarcates the moderate from heavy domains (3). Continuous exercise performed above the GET, within the heavy domain, results in a gradual rise in $\dot{V}O_2$ and blood lactate beyond the third min, but eventually reach a delayed steady-state and exercise can typically be maintained beyond 20 to 30 min (3, 14). Exercise intensities

performed within the severe domain result in continuous increases in $\dot{V}O_2$ and blood lactate until exhaustion is reached, typically within 20 min (14). Previous studies (25, 18) have suggested that CP demarcates the heavy from the severe exercise intensity domains. For example, Poole et al. (25) showed that subjects could complete a 24 minute constant power output ride at CP, but 7 of 8 subjects could not complete a 24 minute ride at CP + 5% of the maximal power. In addition, the blood lactate and $\dot{V}O_2$ responses stabilized during the ride at CP, but continued to rise during the ride at CP + 5%. Furthermore, Jenkins & Quigley (18) showed that during a 30-min ride at CP, the blood lactate concentrations increased during the first 5-10 minutes, but plateaued during the final 20 minutes. Likewise, Brickley et al. (6) found time to failure at CP to be between 20 and 40 minutes. Recently, it has been suggested (3) that the respiratory compensation point (RCP), measured during an incremental test, may represent a similar intensity as CP. Therefore, taken together, previous studies (3, 6, 18, 24) indicated CP and the RCP demarcate the heavy and severe exercise intensity domains in which prolonged exercise, with steady-state $\dot{V}O_2$ and blood lactate responses, can be maintained between 20 and 40 minutes.

The validity and applications of the AWC parameter of the CP model have also been examined (7, 19, 22). The AWC has been shown (19) to be highly correlated with total work completed during maximal exercise. In addition, the anaerobic capacity (AC) measured from the Wingate 30-second all-out test was significantly related to AWC (22). The findings suggested that both the AC and AWC reflect anaerobic energy metabolic capacity and are dependent on the stored energy sources within muscle (i.e., phosphor creatine, muscle glycogen, and the oxygen bound to myoglobin). Furthermore, Bulbulian

et al. (7) examined the use of the AWC parameter in the prediction of distance running performance. The authors (7) indicated superior performance predictions utilizing anaerobic measures in addition to aerobic measures in an otherwise homogenous aerobically trained population. Thus, previous studies (7, 19, 22) have shown the AWC estimates from the CP test to be a valid representation of anaerobic capacity and to have practical implications in the prediction of performance.

Typically, the CP test requires multiple, exhaustive workouts, which may limit the application of the model. Thus, several studies (25, 18, 19) have used different methodological variations of the number of work bouts to determine CP ranging from three to five work bouts. Housh et al. (16) showed that both CP and AWC could be estimated from two constant power output rides to exhaustion using the linear, total work versus T_{lim} model. More recently, a methodological change to the CP test was developed utilizing a single, CP 3-min all-out test (CP_{3min}) (9, 27). The 3-minute duration was selected because it allowed enough time to yield a stable power output during the last 30 seconds of the test, termed the end test power (EP), and hypothesized to reflect CP. In addition, the work performed above the EP, W' , could be calculated. Vanhatalo et al. (27) compared the parameters of the 3-min all-out test (EP and W') to those of the CP total work versus T_{lim} model. The authors (27) reported no difference between the EP or W' estimated from the CP_{3min} test and CP or AWC estimated from total work versus T_{lim} model, respectively. Thus, the authors (27) concluded that CP and AWC could be accurately estimated from a 3-min all-out test.

The CP_{3min} test of Burnley et al. (9) and Vanhatalo et al. (27) provided a less physically demanding protocol compared with the traditional multiple workout model.

The authors (9, 27) methodology, however, required an incremental test to exhaustion prior to the CP_{3min} test to determine the $\dot{V}O_2$ peak and GET. These parameters were used to determine the resistance setting for the 3-min all-out test. Thus, the CP_{3min} test proposed by Burnley et al. (9) and Vanhatalo et al. (27) was not truly a single workout test. In an attempt to improve the applicability of the CP_{3min} test, Bergstrom et al. (4) hypothesized that a single 3-min all-out test with resistance set as a percent body weight could be used to estimate CP and AWC. The authors reported the CP and AWC estimates from the CP_{3min} test, with the resistance set at 4.5% body weight, were not significantly different from CP and AWC estimates from the multiple workout W_{lim} vs T_{lim} model. These findings (2) indicated that CP and AWC could be determined from a single workout, with the resistance set based on body weight, without the need to measure gas exchange parameters during an incremental exercise test to exhaustion.

Recently, Clark et al. (10) further examined the CP_{3min} test protocol. The authors (10) developed criteria for setting the resistance for the CP_{3min} based off a percent body weight that was dependent upon an individual's activity level; 3% for recreationally trained individuals (REC), 4% for anaerobic/aerobic sport athletes (SPORT), and 5% for endurance athletes (END). The authors (10) reported no difference between the CP estimates from the test with a resistance set based on body weight and activity level and the CP estimates from a CP_{3min} test of Burnley et al. (9) and Vanhatalo et al. (27). Thus, currently there are 3 separate recommendations (9, 27, 4, 10) for estimating CP and AWC from a CP_{3min} test. No previous studies, however, have compared estimates of CP and AWC from the 3-min all-out test with the resistance set at 4.5% of body weight, as recommended by Bergstrom et al. (2) and the resistance set as a percent of body weight

dependent upon activity level, as recommended by Clark et al. (10). Thus, it is still unclear if separate recommendations that are dependent upon activity level are necessary for setting the body weight resistance for the CP_{3min} test. Therefore, the purpose of this study was to determine if the CP and AWC estimates from a single, 3-minute all-out test were affected by the percentage of body weight used to set the resistance on a Monark cycle ergometer within three separate training groups (REC, SPORT, and END). Two secondary purposes were also included in this study; 1) to identify where CP values were located relative to the GET and RCP, and 2) determine what body composition characteristics significantly contributed to CP and AWC parameters. Based on previous studies (2, 9, 10, 27), we hypothesized that the resistance setting on the cycle ergometer will have no effect on CP and AWC estimates.

Chapter II: Review of Literature

1. Development of Critical Power Concept

Monod & Scherrer (20)

The purpose of this study was to examine and define the relationship between force or power output (P) and the time to exhaustion (T_{lim}) for intermittent isometric and dynamic muscle actions of local muscle groups (i.e., less than one-third of the whole muscle mass). The authors developed the critical torque and critical power (CP) models. Critical power was defined as the maximum rate a muscle can keep up for a very long time without fatigue. Critical power was determined by measuring total amount of work (W_{lim}) performed during a series of muscular work tests at various, constant power outputs to induce local muscular exhaustion. The W_{lim} was equal to the product of the power output (P) and T_{lim} ($W_{lim} = P \times T_{lim}$). The authors observed a linear relation between W_{lim} and T_{lim} ($W_{lim} = a + b \cdot t_{lim}$). Factor “b”, the slope of the line, represented CP of dynamic work. Factor “a” represented an energetic reserve, termed the anaerobic work capacity (AWC). The AWC was the total amount of work that could be performed above CP. Theoretically, exhaustion will not occur for any power output that is performed below or equal to CP. Based on these findings, the authors suggested the maximum amount of dynamic work a muscle can do in a given time can be determined. Thus, the known work capacity of a muscle can be used to predict the T_{lim} for any power output greater than CP ($T_{lim} = a / P - b$).

Moritani et al. (21)

The purpose of this study was to determine if the critical power (CP) concept could be extended to whole-body exercise, and examine its relationship to anaerobic threshold (AT) and $\dot{V}O_2$ max. The subjects consisted of eight male and eight female college students enrolled in a physical education class. An electrically braked cycle ergometer was used for all the tests. The subjects began with a graded $\dot{V}O_2$ max test to exhaustion for the determination of the $\dot{V}O_2$ max, anaerobic threshold (AT), and the $\dot{V}O_2$ at AT ($AT\dot{V}O_2$). The critical power was then determined from 3 different constant power output rides to exhaustion. The time to exhaustion (T_{lim}) was recorded and the limit work (W_{lim}) was calculated as the product of the power output and T_{lim} for each of the rides. The W_{lim} from the 3 rides was plotted as a function of T_{lim} and defined by the equation $W_{lim} = a + b \cdot t_{lim}$. The CP represented the slope (b) and the anaerobic work capacity (AWC) represented the y-intersect (a). The results from the study indicated a highly linear relationship between W_{lim} and T_{lim} as expressed $W_{lim} = a + b \cdot t_{lim}$ ($r^2 = 0.982 - 0.998$). There was a significant correlation between $AT\dot{V}O_2$ and CP expressed in watts, $AT\dot{V}O_2$ and the $\dot{V}O_2$ at CP ($CP\dot{V}O_2$), and $\dot{V}O_2$ max and CP. In conclusion, the AWC represented the energy contained in phosphorous components and the use of intramuscular glycogen and oxygen bound to myoglobin within the muscle. The CP represented the maximal power a given muscle can perform without fatigue. When power output is greater than CP muscular fatigue may take place. This creates implications towards performance outcomes in sport. The authors concluded that CP appears to represent the maximal rate of work beyond which energy reserves will ultimately be depleted.

Summary:

The critical power (CP) concept for a single muscle or muscle group was developed by Monod & Scherrer (20) and defined as the maximum work rate a muscle can maintain for a very long time without fatigue. The authors determined this by measuring the amount of work (W_{lim}) completed during a series of muscular work tests at various, constant power outputs to induce local muscular exhaustion. There was a linear relationship between W_{lim} and the time to exhaustion (T_{lim}) and that was defined by the regression equation; $W_{lim} = a + b \cdot T_{lim}$. The slope, factor “b”, represented the CP while the y-intercept, factor “a”, represented an energetic reserve known as anaerobic work capacity (AWC). Based on these findings, the authors suggested the maximum amount of dynamic work a muscle can do in a given time can be determined. Moritani et al. (21) expanded the findings of Monod & Scherrer (20), to relate to whole-body exercise. The relationship between W_{lim} and T_{lim} for cycle ergometry was highly linear supporting the hypothesis that CP concept was applicable to whole-body exercise. Practical implications for CP and AWC exist within performance and sport.

2. Parameters of the Critical Power Concept

2.1 Critical Power

Poole et al. (25)

The purpose of this study was to investigate the metabolic and respiratory responses to prolonged, constant-load cycle ergometry both at and slightly above critical power (CP). The metabolic (rectal temperature; blood lactate, pyruvate, norepinephrine, and epinephrine) and respiratory (ventilation [\dot{V}_E], oxygen uptake [$\dot{V}O_2$], CO₂ output

[$\dot{V}CO_2$], blood pH, PCO_2 , HCO_3^-) responses during constant-load cycling were examined to determine the factors that may underlie the continuous increase in $\dot{V}O_2$ at power outputs $>CP$. The subjects for the study were eight healthy, young males none of whom was involved in regular physical training. All tests were performed on an electromagnetically braked cycle ergometer starting with an incremental exercise test to exhaustion for the estimation of lactate threshold (T_{LAC}) and $\dot{V}O_2$ max. To define the power (P) – duration (T) relation for high-intensity exercise, each subject completed five different constant power output rides to fatigue. Time to fatigue was measured as the time from the dropping of the resistance load to the point at which the subject could no longer continue cycling. Only one test was completed on a given day with a randomized sequence. Two further constant power output rides at CP and CP + 5% of max power from the incremental test were completed on different days following the completion of the prior five tests. The results indicated that all subjects were able to complete the constant-load test conducted at CP for 24 minutes, and all but 1 subject fatigued prior to 24 minutes with the $>CP$ test. The $\dot{V}O_2$ response correlated most with the lactate response; both responses stabilized during the CP test while continuing to rise during the $>CP$ test. Lactate levels during the $>CP$ test indicated a sharp, continual increase until the cessation of exercise differing from the lactate levels at the CP test which had a slight increase and then leveling off to ride completion. The authors' concluded that between T_{LAC} and CP, $\dot{V}O_2$ can attain a steady state and hence allow the performance of prolonged exercise. Secondly, exercise performed at a power output above CP results in exhaustion that is described as a hyperbolic function of P-T curve, with $\dot{V}O_2$ eventually reaching $\dot{V}O_2$ max. Although numerous factors are likely to contribute to the $\dot{V}O_2$ increase, lactate

metabolism appears to be one possible explanation. Therefore, the authors concluded that CP represents the highest power output where $\dot{V}O_2$ and blood lactate will reach a steady state and provides the demarcation between heavy-intensity exercise and severe-intensity exercise.

Jenkins & Quigley (18)

The purpose of this study was two-fold: 1) -to determine the validity of critical power (CP) as a measure of the work rate that can be maintained for a very long time without fatigue and; 2) -to determine whether this corresponded with the maximal lactate steady-state ($LA_{ss,max}$). The subjects consisted of eight highly trained endurance cyclists (maximal oxygen uptake $74.1 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$); the first visit was a $\dot{V}O_{2max}$ test with blood lactate samples taken at 3-minute intervals until exhaustion followed by CP testing using four separate exercise tests at a constant power output to exhaustion. The work limit (W_{lim}) versus time limit (T_{lim}) was plotted with a linear regression equation. The CP was defined as the slope and anaerobic work capacity (AWC) as the y-intercept of the W_{lim} versus T_{lim} relationship. The final visit was a 30-minute ride at CP with blood lactate measurements taken at 0, 5, 10, 20, and 30 minutes into exercise. The results indicated that for during the 30 min ride at CP the mean fixed power output (W) was decreased by 6.7% to maintain exercise. The validation ride indicated that CP was just slightly greater than the power output that could be tolerated for up to 30 minutes for most subjects. There was a rapid increase in blood lactate concentrations during the first 5-10 minutes of exercise, but then a levelling out occurred during the last 20 minutes indicating CP slightly overestimated $La_{ss,max}$. Mean lactate concentration was significantly correlated to

AWC. In conclusion, CP is a valid representation of the maximal exercise intensity that can be maintained for up to 30 minutes and that blood lactate concentrations remain relatively higher during extended exercise than during an incremental test.

Brickley et al. (6)

The purpose of this study was to examine the physiological responses (heart rate, oxygen consumption, and blood lactate concentrations) to exercise at critical power (CP). The authors hypothesized that there would be no increase in heart rate, oxygen consumption, and blood lactate concentrations during exercise at CP and that exercise time at CP would be at least 60 minutes. The subjects consisted of seven trained males familiar with cycle ergometry. The subjects completed five exercise tests; first, $\dot{V}O_{2\max}$ was determined using an incremental protocol test, then three constant load tests were used to determine CP, and a final test to exhaustion at CP was performed. All tests were completed on different days with at least 24 hours of rest given between tests and all tests were completed within 14 days. The results from the study indicated there were a significant increase ($p < 0.05$) from the original mean value measured after a 5-10 min warm-up and the mean value after 20 minutes of exercise at CP for oxygen uptake, heart rate, and blood lactate concentration. Time to failure at CP ranged from 20 to 40 minutes. The authors concluded that exercise performed at CP is both non-sustainable and non-steady state. The work rate when exercising at CP was approximately 80% $\dot{V}O_{2\max}$ and a physiological steady state was not maintained. The authors stated that the previous definition of CP (the maximum rate that can be maintained for a very long time without fatigue) was inaccurate and that a more appropriate definition based on their findings was

the highest, non-steady-state intensity that can be maintained for a period in excess of 20 minutes, but generally no longer than 40 minutes (6).

2.2 Anaerobic Work Capacity

Jenkins & Quigley (19)

The purpose of this study was to examine the relationship between the y-intercept from the critical power (CP) test and measures of anaerobic work capacity (AWC) gained from repeated, maximal exercise. The measures included total work accomplished, maximal blood lactate, and post-exercise venous blood pH. The subjects for the study were nine moderately active males. All tests were completed on a Monark cycle ergometer. The first testing date included a graded incremental test to fatigue to determine $\dot{V}O_2$ max. Two days later, CP was determined from three cycle ergometry tests to exhaustion at different, constant power outputs with each test separated by 3 hours. The 3 values of work limit and time limit for each subject from each test were used in a regression to form the linear equation. The final testing day included five 1 minute cycle bouts each separated by 5 minute periods of passive recovery to assess AWC. The accumulated work over the five bouts was calculated taking into account pedal revolutions, applied resistance, and the work necessary to rotate the flywheel through one complete cycle. Capillary blood was assessed after the 4-5 minutes of passive recovery following each bout. Prior to exercise and within 90 seconds of completing the final bout venous blood was sampled. The results indicated that the y-intercept was significantly correlated with total work completed in the maximal interval exercise test ($r=0.74$, $p<0.05$). Significant correlations were observed between post-exercise venous blood pH

and total work ($p < 0.01$) and between venous blood pH post-exercise and the y-intercept ($p < 0.01$). The results suggested that those individuals with a high y-intercept were able to work harder during the interval test when compared to those subjects with lower values. The authors concluded that the y-intercept derived from the CP curve was related to performance over five 1 minute maximal exercise bouts. The results support the theory that the y-intercept represents anaerobic work capacity and is a useful indicator of the ability to perform intermittent, high intensity work.

Nebelsick-Gullett et al. (22)

The purpose of this study was to determine the relationship between anaerobic work capacity (AWC) and anaerobic capacity (AC) from the critical power (CP) and Wingate tests, respectively. The secondary purpose was to determine the test-retest reliability of the critical power test developed by Moritani et al. (20) and modified by Bulbulian et al. (7). The subjects for the study were 25 females who were moderately to highly active exercising 2-3 days and 5-7 days per week respectively. The first visit included a Wingate anaerobic test performed on a Monark cycle ergometer to measure AC. To measure CP, the subjects performed three dynamic exercise bouts at different, constant power loadings. Approximately 30 minutes or longer were allowed between each of the three tests to allow the heart rate to return within 5 beats per minute of the pre-exercise value. Time limit (TL) was recorded to the nearest 0.1 second and work limit (WL) was calculated by multiplying power (P) and TL. Critical power was the power output corresponding to the slope of the WL-TL relation. Reliability was measured using test-retest procedures performed by all subjects. The results indicated a highly linear

relation between WL and TL ($r^2=0.98-1.00$). The AC and AWC were significantly related ($r=0.74$, $p<0.05$). Test-retest correlations and standard error of the estimate for CP and AWC were $r=0.94$, $SEE=12$ watts and $r=0.87$, $SEE=1358$ joules, respectively. In addition, there were no mean differences between test-retest values for CP or AWC ($p>0.05$). The significant relation between AWC and AC found in the present study further supports the validity of AWC as a measure of anaerobic capacity. The y-intercept of the WL-TL relation represents AWC of a muscle group and was dependent upon energy sources stored within the muscle. The results indicate that the CP test provides a valid and reliable estimation of anaerobic capabilities as well as the maximal rate of fatigueless work.

Bulbulian et al. (7)

The purpose of this study was to examine the role of anaerobic factors in distance running performance and whether anaerobic work capacity (AWC) may be a discriminator of success in running performance in an otherwise aerobic homogeneous group of endurance athletes. The subjects in the study were 12 male cross-country runners from a NCAA division I school. Standardized aerobic and anaerobic laboratory evaluation tests were administered to measure maximal aerobic capacity ($\dot{V}O_2$ max), ventilatory threshold (T_{vent}), running economy (RE), defined as the oxygen consumption when running standardized treadmill speeds, anaerobic work capacity (AWC) determined using the critical power (CP) test, and anaerobic power output (APO) determined using the Margaria-Kalamen Power Test. The dependent variable of an 8.05-km race time was also collected from a pre-season, 20-team competition. $\dot{V}O_2$ max and T_{vent} were measured

using an incremental treadmill test to exhaustion. RE was measured at 2 predetermined speeds each trial lasting 6 minutes. Four consecutive 1-minute samples were recorded during the last 4 minute of each RE trial and the last 3 values were averaged to obtain the criterion measure. AWC was determined from three dynamic exercise tests on a cycle ergometer at different, constant power outputs to exhaustion. Limit time (T_{lim}) and limit work (W_{lim}) were recorded for each test and the W_{lim} was plotted against T_{lim} where the slope represented CP and the y-intercept represented AWC. The Margaria-Kalamen Power Test to determine APO included timing mats on the third and ninth step of a staircase measuring time between activation of the two mats. A STEPWISE multiple regression analysis was used to determine which variable/s best predicted performance. The 8.05-km finish time was the dependent variable. The analysis demonstrated a substantial contribution to performance by anaerobic measures. The one variable model with T_{vent} as the independent variable was not significant ($p>0.08$). The two variable model that used CP and AWC explained 48% of the variance in 8.05 km finishing time and was significant ($p<0.05$). The third variable was $\dot{V}O_2$ max and significantly increased the R^2 with total variance of 76%. The results indicated that AWC made a major contribution to the R^2 improvement (58%). In conclusion, a multifactorial approach should be used when predicting running performance, however the role of the anaerobic system should not be overlooked. In an aerobically homogenous group of runners the athlete with the best suited anaerobic system may have an advantage.

Summary:

Previous studies (18, 25) have suggested that exercise at or below critical power (CP) results in steady-state values for blood lactate and $\dot{V}O_2$ levels, while exercise

performed above CP the responses will not stabilize and continued to increase until exhaustion. For example, Poole et al. (25) showed that subjects could complete a 24 minute constant load ride at CP, but 7 of 8 subjects could not complete a 24 minute ride at CP + 5% power. Blood lactate and O₂ responses were stabilized during the CP ride while continuing to rise during the >CP ride. Jenkins & Quigley (18) showed that during a 30-min ride at CP, the subjects had an increase in blood lactate concentrations during the first 5-10 minutes, but a leveling out during the final 20 minutes. Brickley et al. (6) found CP exercise to be above lactate threshold and non-steady-state when hypothesizing for a ride equal or greater than 60 minutes. Therefore, taken together, previous studies (6, 18, 25) indicated CP represents a marker between heavy and severe exercise in which prolonged exercise can be maintained between 20 and 40 minutes.

The validity and applications of the anaerobic work capacity (AWC) parameter has also been examined by previous studies (7, 19, 22). It was shown (19) that AWC was highly correlated with total work completed during maximal exercise. In addition, the anaerobic capacity (AC) measured from the Wingate 30-second all-out test was significantly related to AWC (22). Both the AC and AWC are dependent on the stored energy sources within muscle. Bulbulian et al. (7) found that superior anaerobic measures may be used to predict distance running performance in an otherwise homogenous aerobic population. Thus, previous studies (7, 19, 22) have shown the AWC estimates from the CP test to be a valid representation of anaerobic capacity and to have practical implications in the prediction of performance.

3. Protocol Variations

3.1 Mathematical Models

Gaesser et al. (13)

The purpose of this study was to compare parameter estimates and goodness of fit (r^2) for the estimates of critical power (CP) and anaerobic work capacity (AWC) from five different mathematical models which included the; two-parameter nonlinear, three-parameter nonlinear, linear total work (power output [P] · time to exhaustion) · time to exhaustion (Linear P·t), linear P, and exponential (EXP). The hypothesis was that linear and nonlinear regression analysis of the power-endurance relationship for high-intensity exercise would produce significantly different estimates for CP and AWC. Sixteen male subjects who were physically active, but not cyclists, participated in the study starting with an incremental test to volitional fatigue on an electrically-braked cycle ergometer to identify power outputs to be used to generate the power-endurance time relationship for high-intensity exercise. Five to seven exercise tests were then performed at a set power output to exhaustion; 3-5 rides lasting approximately 1-10 min and 2 rides lasting 10-20 minutes. Six subjects underwent additional testing to determine long-term exercise ventilatory threshold (LTE T_{vent}). The r^2 values for all models were very high (range = 0.96 – 1.00). There were significant differences among CP and AWC estimates from all five models. Only the three-parameter nonlinear model produced an estimate of CP that was not significantly different from the LTE T_{vent} . Based on these findings, the authors suggested the three-parameter non-linear model was superior for predicting the highest sustainable power output. Any of the five models can be used to differentiate among

individuals with regard to performance, but when assessing physiological parameters, such as LTE T_{vent} , the three-parameter nonlinear model is superior.

Housh et al. (17)

The purpose of this article was to examine the effects of mathematical modeling on critical velocity (CV) estimates and the oxygen consumption ($\dot{V}O_2$), heart rate (HR), and plasma lactate values that corresponded to the five CV estimates. The five models included two linear models, linear total distance (Linear-TD) versus time to exhaustion and linear velocity versus the inverse of time to exhaustion (Linear-V), two nonlinear models; the nonlinear, two-parameter (Nonlinear-2) and nonlinear, three-parameter (Nonlinear-3) models; and one exponential model (EXP). CV is the treadmill analog of critical power (W_{crit}) for synergistic muscle groups and cycle ergometry. The CV is determined from multiple exhaustive runs at different velocities from which the hyperbolic velocity/time relationship is determined. Ten male subjects who exercised regularly, but were not highly trained participated in the study. The subjects completed four randomly ordered treadmill runs to exhaustion at different velocities with run time lasting between 2-12 minutes for the determination of the CV and AVR. The results indicated there were significant differences among the mean CV, $\dot{V}O_2$, HR, and plasma lactate values for the five models. The values for $\dot{V}O_2$ and HR that corresponded to each of the five CV estimates for each subject were determined using linear regression from the relationships of $\dot{V}O_2$ and HR versus running velocities recorded during the maximal graded treadmill test. The plasma lactate values corresponding to the CV estimates for each subject were determined using power curve analyses (ax^b) from the relationship

between the plasma lactate and running velocities from the maximal graded treadmill test. Post-hoc comparisons indicated that the Nonlinear-3 model produced a significantly lower mean CV estimate than the other models. The Linear-TD, Linear-V, and Nonlinear-2 models resulted in mean CV estimates that were very similar and differed by only $0.2 \text{ km}\cdot\text{hr}^{-1}$. Nonlinear-3 and EXP models resulted in mean CV estimates that differed by $2.5 \text{ km}\cdot\text{hr}^{-1}$. Based on the results from this study the five mathematical models produce significantly different CV estimates and more research needs to be done to produce the most valid estimate of the marker point between heavy and severe exercise.

Bull et al. (8)

The purposes of this study were to re-examine the findings of Gaesser et al. (13) using the same five mathematical models for estimating critical power (CP) and to determine to time exhaustion (T) during cycle ergometry at the lowest CP estimate from the five models. The five mathematical models included the; 1) linear total work (TW) versus T (Linear-TW), 2) linear power (Linear-P), 3) two-parameter nonlinear (Nonlinear-2), 4) three-parameter nonlinear (Nonlinear-3) and, 5) exponential (EXP) model. The subjects were nine males who were not advanced cyclists. Each subject completed eight or nine trials with each trial being separated by more than 24 hours. The first trial was a maximal incremental test to exhaustion on an electronically braked cycle ergometer as close to $60 \text{ rev}\cdot\text{min}^{-1}$ as possible. The power output and heart rate attained at exhaustion were considered to be the subject's peak power (P_{peak}) and peak heart rate (HR_{peak}). The subjects then performed five or six randomly ordered trials at $60 \text{ rev}\cdot\text{min}^{-1}$.

If none of the five trials reached 10 minutes then a sixth trial was performed at a power output estimated to achieve T greater than 10 minutes. The mathematical model that produced the lowest estimate of CP would then be used as the selected power output (P) for the final two trials at CP (CP-1 and CP-2). The results from the study indicated a significant difference between the CP estimates of the five models. The r^2 values for the five models ranged from 0.87 – 1.00. The post-hoc analysis indicated that the Nonlinear-3 model produced a significantly lower mean CP estimate than the other models. The Nonlinear-3 estimate of CP was the selected P for CP-1 and CP-2. Two of the nine subjects could not complete 60 minutes of cycling during CP-1 or CP-2. The mean rate of perceived exertion (RPE) values for the end of CP-1 and CP-2 indicated the subjects were exercising “very hard” to “very, very hard” (CP-1 RPE = 19 ± 1 ; CP-2 RPE = 17 ± 3). The authors support the conclusion that CP does not represent a “fatigueless task” as proposed by Monod and Scherrer (19) based on the subjects’ inability to complete 60 minute trials at CP.

Bergstrom et al. (4)

The purpose of this article was to examine the estimates of critical power (CP) and anaerobic work capacity (AWC) from the 2- and 3- parameter models (two linear, two nonlinear, and one exponential) and those from the CP 3-minute all-out (CP_{3min}) test. The authors stated four hypotheses: 1) there would be significant differences in the parameter estimates among the six models; 2) the Nonlinear-3 model would produce the lowest estimate of CP and the EXP model the highest; 3) the Nonlinear-2 model would produce the highest estimates of AWC and the Linear-P and Linear-TW models the

lowest and; 4) the estimates of CP and AWC from the CP_{3min} test and the Linear-P and Linear-TW models would not be significantly different. The subjects included nine college-aged recreationally trained individuals. All tests were performed on a calibrated Lode electronically braked cycle ergometer. Each subject completed 6 exhaustive cycling tests with 24-48 hours between each test. The first visit included an incremental cycle ergometer test to exhaustion to determine $\dot{V}O_{2peak}$ and gas exchange threshold (GET). Four randomly ordered constant power output rides to exhaustion were then completed to determine CP and AWC from the 2- and 3-parameter mathematical models. The final visit estimated CP and AWC from the 3-minute all-out test. The resistance for the test was set using the linear mode of the electronically braked cycle ergometer (linear factor = power/ [preferred cadence]²). The results indicated there were significant differences among the means of the 6 estimates of CP with post hoc comparisons indicating that the Nonlinear-3 model produced the lowest estimates of CP. In addition, the EXP model and CP_{3min} test produced the highest estimates of CP. There were significant differences between the 5 estimates of AWC with post hoc comparisons indicating the Nonlinear-2 and Nonlinear-3 models produced significantly higher estimates of AWC. The authors concluded that the Nonlinear-3 model could represent the true demarcation of the heavy and severe exercise intensity domains and accurately estimates the anaerobic capabilities.

3.2 Work Bouts

Housh et al. (16)

The purpose of this article was to determine the number of powerloadings necessary to achieve an accurate estimate of critical power (CP) and anaerobic work

capacity (AWC). The subjects consisted of 12 males. Four workbouts to exhaustion at different powerloadings were completed on two testing dates. The two trials were separated by about 30 minutes to allow the subject's heart rate to return to within 10 beats per minute of the resting heart rate. The results from this study indicated that CP and AWC could be accurately estimated using only two work bouts. The use of the highest and lowest powerloadings resulted in estimates of CP and AWC with the highest correlations ($r = 0.99$ and $r = 0.98$) and the lowest standard error of estimates ($SEE = 1.68$ W) when compared to the values estimated using all four powerloadings. It was recommended that the time limit (T_{lim}) values for the two workloads range from about 1 to 10 minutes and differ by approximately 5 minutes or more. The two middle workloads (2 and 3) differed in T_{lim} by a mean of only 1.14 minutes and was likely the reason for the lower accuracy and correlations (CP $r=0.80$, $SEE=39.04$ W; AWC $r=0.51$, $SEE=11,834$ W). The findings of this study suggest that only two workloads, the highest and lowest, are necessary to estimate an accurate measurement of CP and AWC reducing the stress on both subject and tester.

Summary:

Currently there are five mathematical models used to estimate critical power (CP) and anaerobic work capacity (AWC) (13). Previous studies (4, 8, 13, 17) have shown differences in the estimates of CP and AWC among these models. Gaesser et al. (13) compared the five models to the long-term ventilator threshold (LTE T_{vent}) which represents the highest sustainable power output. When comparing the five mathematical models for predicting CP and AWC the three parameter nonlinear model (Nonlinear-3)

was the only model not significantly different from the LTE T_{vent} . Housh et al. (16) compared the estimates from the five models with critical velocity (CV), the treadmill analog of critical power. There were significant differences between the five estimates and the nonlinear-3 model produced significantly lower estimates than the other methods. Bull et al. (8) furthered the research by choosing the lowest of the five model estimates from his study as the CP to be used for two 60 minute validation rides. The Nonlinear-3 model resulted in the lowest estimate of CP and highest estimate of AWC of the five mathematical models, however time limit for exercise at the CP from Nonlinear-3 did not reach the hypothesized 60 minutes for a validation ride. Bergstrom et al. (4) chose to examine the five models compared to a different methodology of the CP 3-min all-out test with resistance based on the linear factor. The parameter estimates were significantly different between models and the nonlinear-3 model produced the lowest estimate of CP. Because nonlinear-3 results in the lowest CP estimate it may represent the true demarcator of heavy and severe exercise according to previous literature (4, 8, 13, 17). Throughout previous literature (22, 25) there has been variation in test protocol regarding the number of powerloadings; two, three, or four work bouts; necessary to accurately estimate values of critical power (CP) and anaerobic work capacity (AWC) Housh et al. (17) examined the number of powerloadings necessary to accurately estimate CP. The authors (17) concluded that two work bouts on the cycle ergometer may accurately predict CP and AWC. Conservatively the time limit for each bout should range from 1 to 10 minutes and be separated by approximately 5 minutes. CP protocol would be simplified by methodologically utilizing a two work bout test.

4. Three Minute All-Out Test

Burnley et al. (9)

The purpose of this study was to determine if a 3-minute all-out cycling test would provide a measure of peak oxygen uptake ($\dot{V}O_{2\text{ peak}}$) and estimate the maximal steady-state power output. Three hypotheses were tested; 1) 3-min all-out exercise test would provide a reproducible power output profile; 2) the test would elicit a peak $\dot{V}O_2$ that was not different from measured $\dot{V}O_{2\text{peak}}$ in an incremental test; and 3) the power output during the last 30 seconds of the test would be a marker between heavy and severe exercise. Eleven recreationally trained individuals who were accustomed to high-intensity exercise participated in this study. The study required six laboratory visits with a minimum of 24 hours between each test. The first visit was a $\dot{V}O_{2\text{ peak}}$ incremental test to exhaustion. The second visit was a 3-min all-out familiarization test. The third and fourth visits involved the 3-min all-out tests. The final two visits were rides to 30 minutes or exhaustion at constant work rates 15 W above or below the end-power of the 3-min trial in random order. The 3-min tests were done at a preferred cadence between 80-90 $\text{rev}\cdot\text{min}^{-1}$ using the linear factor of the Lode ergometer. The results indicated that the $\dot{V}O_{2\text{ peak}}$ from the incremental test was not significantly different from the $\dot{V}O_{2\text{ peak}}$ measured during the 3-min test. The two 3-min all-out trials end-test power outputs were not significantly different from each other. The power output versus time profile for the 3-min all-out tests displayed a rapid decline in power output during the first 60 seconds, but a leveling out to a relatively steady-state during the last 60 seconds. Nine of the 11 subjects were able to complete the trials to 30 minutes at 15 watts (W) below the end-test power, but none of the subjects were able to complete to 30 minutes at 15 W above the

end-test power. The authors' hypothesized that if the 3-min test could be continued until the levelling out to a steady-state then the end-power would demarcate the heavy- and severe-intensity domains representing critical power (CP).

Vanhatalo et al. (27)

The purpose of this study was to compare the parameters of the power-duration relationship derived from a 3-minute all-out cycling test with those derived from a series of five exhaustive exercise bouts from the conventional method of critical power (CP) determination. The hypothesis was that the power output attained at the end of a 3-minute all-out cycling test would be equivalent to critical power. The subjects included 10 habitually active individuals accustomed to high-intensity exercise. The experiment included eight visits to the laboratory with 24 hours between tests. The first visit included an incremental test to determine $\dot{V}O_{2\text{ peak}}$ and gas exchange threshold (GET). The second visit involved a 3-min all-out familiarization test. During the third visit the subjects performed the 3-min all-out test and the last five visits consisted of five constant power output rides to exhaustion to determine CP and W' . Results from the study supported the hypothesis; the power output in a 3-min all-out cycling test fell to a steady state near the last 45 seconds of the test and the average of the last 30 seconds was not significantly different from the independently measured CP using the conventional method.

Bergstrom et al. (2)

The purpose of this article 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. Twelve moderately-trained subjects, 6 males and 6 females, participated in the study which required 8 laboratory visits. The first visit included an incremental cycle ergometer test to exhaustion to determine $\dot{V}O_2$ peak and the gas exchange threshold. The next 4 visits included different constant power output rides to exhaustion to determine CP and AWC. Critical power and AWC were defined as the slope and y-intercept, respectively, from the linear, total work (W_{lim}) versus time limit (T_{lim}) relationship (CP_{PT}). The CP 3-min all-out test (CP_{3min}) was performed against a fixed resistance on an electronically braked cycle ergometer. In addition, two separate CP3-min all-out tests were performed on a Monark cycle ergometer with the resistance set at 3.5% ($CP_{3.5\%}$) and 4.5% ($CP_{4.5\%}$) of the subject's body weight. There were no significant difference between the CP estimates for the CP_{PT} , $CP_{3.5\%}$, and $CP_{4.5\%}$ tests. The CP estimates from CP_{3min} was significantly greater than those from CP_{PT} and $CP_{3.5\%}$. For AWC, there were no significant differences between CP_{PT} , CP_{3min} , and $CP_{4.5\%}$. The AWC estimates from CP_{PT} and CP_{3min} were significantly greater than that from the $CP_{3.5\%}$. The authors concluded that CP and AWC could be estimated from a single, 3-min all-out test on a Monark cycle ergometer with the resistance set at 4.5% of the subject's body weight.

Clark et al. (10)

The purpose of this study was to evaluate a new procedure of establishing the load for the critical power (CP) 3-min all-out exercise test (3 MT) using a percentage of body mass (% BM). All tests were completed on an electronically braked cycle ergometer. Fifteen subjects, 12 females and 3 males, completed all the trials during 3 separate

laboratory visits. The subjects' activity levels were 8 off-season, collegiate hockey players, 1 distance runner, and 3 recreationally active individuals. The first laboratory visit required completing a custom graded exercise test (GXT) to establish gas exchange threshold (GET) and $\dot{V}O_{2\max}$. The second visit was a 3 MT using a load derived with the linear factor; linear factor = 50% Δ (average power between 2 parameters $\dot{V}O_{2\max}$ and GET expressed in watts)/preferred cadence squared (rpm). The third and final visit used resistance load % BM based on activity level. The resistances were selected as a %BM using the following criteria; 3% BM for recreationally active individuals, 4% BM for aerobic and anaerobic athletes (e.g., ice hockey or soccer players), and 5% BM for endurance athletes. Critical power (CP) and anaerobic work capacity (AWC) were determined for each test. There were no differences in the CP estimates derived from the resistance set using the linear factor or the % BM. The estimates of AWC between methods were not significantly different, but were less reliable ($\alpha = 0.43$, compared to CP $\alpha = 0.97$). The authors concluded that the estimates of CP and AWC from the test with the resistances set as a % BM test were similar to the estimates from the test with the resistance set using the linear factor, and may therefore eliminate the need for an exhaustive GXT and multiple laboratory visits. With a more simplistic method of determining CP and AWC the 3 MT protocol is a more practical method for strength and conditioning program design.

Summary:

A methodological change to the critical power (CP) test was developed utilizing a single, 3-min all-out test. The 3-minute test was chosen by Burnley et al. (9) because it

allows enough time to yield a stable power output during the last 30 seconds of the test which is close to the power output at which the marker of heavy-severe exercise would occur. The relationship between power output and time to exhaustion is hyperbolic and is defined by CP; the highest sustainable work rate; and anaerobic work capacity (AWC); the maximum amount of work that can be performed above CP. The 3-minute all out profile shows rapid decline in the first 60 seconds, but a leveling out during the last 60 seconds with a repeatable profile. In the longer all-out test the power output would descend to an end-test power associated with the transition from the heavy to severe exercise domain based on the hyperbolic character of the power-duration curve.

Vanhatalo et al. (27) compared the 3-minute all-out profile, specifically the mean power output during the last 30 seconds, to CP. The results concluded there was no difference between the power output average during the last 30 seconds of the 3-minute test and CP. Burnley et al. (9) and Vanhatalo et al. (27) methodologies required an incremental test to exhaustion prior to the 3-min all-out test to determine the resistance setting for the 3-min test. Bergstrom et al. (4) hypothesized that a single work bout with resistance set at a percent body weight would yield a CP estimate that was no different from the CP model without requiring an incremental exercise test to exhaustion. The CP estimate from the 3-minute all-out test with the resistance set at 4.5% body weight was not significantly different from CP estimate from work vs time method indicating that CP can be determined from a single workout, with the resistance set based on body weight, and without the need for an incremental test or the use of expensive metabolic testing equipment. Clark et al. (10) developed the procedure of determining resistance for the 3-min all-out test based off a percent body weight depending on activity level (3% for

recreationally trained individuals, 4% for anaerobic/aerobic sport athletes, and 5% for endurance athletes). There was no difference between the CP estimates from the test with a resistance set based on body weight and activity level and the CP estimates from a 3 min-all out test of Burnley et al. (9) and Vanhatalo et al. (27). Thus, currently there 3 separate recommendations (4, 9, 10, 27) for estimating CP and AWC from a 3-min all-out test. Therefore, further research is needed to examine a single recommendation for determining resistance for the 3-min all-out test.

CHAPTER III: METHODS

Subjects

Twenty-one subjects (11 women and 10 men) between the ages of 18.6 and 27.5 years old were recruited for this study. Seven subjects (4 females, 3 males; mean \pm SD age: 22.0 ± 2.4 years; height: 171.7 ± 9.3 ; body mass: 73.1 ± 22.1 kg) were placed within the REC group, based on the American College of Sports Medicine definition of recreationally trained as an individual who engages in $150 \text{ min} \cdot \text{wk}^{-1}$ of moderate intensity exercise (23). Seven subjects (3 females, 4 males; mean \pm SD age: 22.3 ± 2.5 years; height: 169.6 ± 9.6 cm; body mass: 80.9 ± 21.3 kg) who were members of the campus club rugby or soccer team were placed within the SPORT group. Seven subjects (3 females, 4 males; mean \pm SD age: 23.5 ± 2.6 years; height: 173.7 ± 5.2 cm; body mass: 64.0 ± 8.4 kg) were endurance athletes who averaged 24.1 ± 7.9 miles $\cdot \text{wk}^{-1}$ running and were placed within the END group. This study was approved by the University Institutional Review Board for Human Subjects. All subjects completed a health history questionnaire and signed a written informed consent document before testing.

Experimental Approach and Design

The subjects visited the laboratory on three occasions. During the first visit, resting heart rate and blood pressure were taken prior to resting electrocardiogram (ECG). Following the ECG, the subjects performed an incremental cycle ergometer test to exhaustion for the determination of $\dot{V}O_2$ peak and the GET. Before either the second or third visit all subjects completed a total body dual-energy X-ray absorptiometry (DXA) scan. A urine pregnancy test immediately prior to DXA scan was administered to ensure the female subjects were not pregnant. During visits two and three, the subjects

performed one of two, randomly ordered, CP_{3min} tests to estimate CP and AWC. The resistance for the CP_{3min} was set at 4.5% body weight ($CP_{4.5\%}$) or was set based on the subjects activity level (CP_{ACT}): 3% for recreationally trained individuals ($CP_{3\%}$ test), 4% for anaerobic/aerobic sport athletes ($CP_{4\%}$ test), and 5% body weight for endurance athletes ($CP_{5\%}$ test).

Determination of $\dot{V}O_2$ peak (Visit 1)

Each subject performed an incremental test to exhaustion on a calibrated Lode electronically-braked cycle ergometer (Corival, Groningen, The Netherlands) at a pedal cadence of $70 \text{ rev} \cdot \text{min}^{-1}$. The ergometer seat height was adjusted so that the subject's legs were near full extension at the bottom of the pedal revolution. Toe cages were used to maintain pedal contact throughout the test. All subjects wore a nose clip and breathed through a mouthpiece. Expired gas samples were collected and analyzed using a calibrated metabolic cart. The gas analyzers were calibrated with room air and gases of known concentration prior to all testing sessions. The O_2 , CO_2 , and ventilatory parameters were expressed as 30-s averages. In addition, the heart rate was recorded with a Polar Heart Rate Monitor (Polar Electro Inc., Lake Success, NY) that was synchronized with the metabolic cart. The test began at 50 W and the power output increased by 30 W every 2 min until voluntary exhaustion or the subject's pedal rate decreased below $70 \text{ rev} \cdot \text{min}^{-1}$ for more than 10 seconds, despite strong verbal encouragement. Verbal encouragement was provided throughout the test.

The GET was determined using the V-slope method described by Beaver et al (1). Specifically, the GET was defined as the $\dot{V}O_2$ value corresponding to the intersection of two linear regression lines derived separately from the data points below and above the

breakpoint in the $\dot{V}CO_2$ versus $\dot{V}O_2$ relationships (Figure 1). The RCP was determined using the $\dot{V}E$ versus $\dot{V}CO_2$ relationship described by Beaver et al. (1). The RCP was defined as the $\dot{V}O_2$ value corresponding to the intersection of two linear regression lines derived separately from the data points below and above the breakpoint in the $\dot{V}E$ versus $\dot{V}CO_2$ relationships (Figure 2). Power output values from the incremental test were then plotted against $\dot{V}O_2$ values, and the regression equation derived was used to determine the power output at the GET and RCP.

CP_{3min} test (CP_{4.5%} or CP_{ACT}) (Visit 2 & 3)

Prior to the test, the subjects completed a warm-up at ~50 W for 5 min followed by 5 min of rest. The test began with unloaded cycling for 3 min followed by a 3 min all-out effort at the determined resistance. The subjects were instructed to increase the pedaling cadence to 110 rev·min⁻¹ in the last 5 s of the unloaded phase and then maintain the cadence as high as possible throughout the 3-min all-out test. To prevent pacing and ensure an all-out effort, the subjects were not aware of the elapsed time and strong verbal encouragement was provided. The resistances were randomized between CP_{4.5%} and either CP_{3%}, CP_{4%}, or CP_{5%} of body weight, for recreationally trained, anaerobic sport athletes, and endurance trained athletes, respectively. The subjects were not aware of the elapsed time or resistance setting. The estimates for CP and AWC from the CP_{3min} tests were estimated from the power versus time relationships (Figure 3). The CP was the average power output over the final 30 seconds of the test and the AWC was calculated as the work done above CP using the following equation (10):

$AWC = 150 \text{ s} (P_{150} - CP)$, where AWC is expressed in joules and P_{150} is the mean power output for the first 150 seconds of the test, and P_{150} and CP are expressed in watts.

Body Composition Assessment

Each subject underwent a single total body DXA scan to provide measures of body composition. Total body DXA scans were performed using a Lunar Prodigy iDXA (Lunar Inc., Madison, WI) bone densitometer. The subjects were instructed to remove all objects such as jewelry or eyeglasses and wore t-shirt and shorts containing no metal during the scanning procedure. All scans were analyzed by a single trained investigator using the Lunar software version 13.10. DXA bone mineral content (BMC; g), DXA bone mineral density (g/cm^2), DXA fat-free mass (FFM; kg), DXA fat mass (kg), and DXA mineral-free lean mass (LBM; kg), and DXA percent fat (%Fat) were assessed. Total thigh mineral-free lean mass (LTM) was delineated using previously published anatomical boundaries for both left and right thighs (28).

Statistical analysis

The mean differences between CP and AWC estimates from the CP_{4.5%} and the CP_{ACT} (CP_{3%}, CP_{4%}, CP_{5%}) were examined using separate paired samples t-tests. The relationship between the two estimates of CP and AWC (from the CP_{4.5%} and CP_{ACT} tests) were described using separate Pearson product-moment correlation coefficients. In addition, separate Bland and Altman analyses (5) were used to assess the agreement between the CP_{4.5%} and CP_{ACT} as well as the AWC_{4.5%} and AWC_{ACT} (AWC_{3%}, AWC_{4%}, AWC_{5%}). The 95% limits of agreement (LOA) were calculated. Mean differences among the CP_{ACT}, CP_{4.5%}, GET, and RCP for each activity group were examined using separate, one-way repeated measures ANOVAS with least significant difference (LSD) pairwise

comparisons. A zero order correlation matrix was used to examine the relationship among CP_{ACT} , $CP_{4.5\%}$, GET, RCP, AWC_{ACT} , and $AWC_{4.5\%}$ for each activity group.

Mean differences among the $\dot{V}O_2$ peak, the GET, peak power during the $CP_{4.5\%}$ test (defined as the highest 5 s average power output during the test, body mass (kg), % fat, and $CP_{4.5\%}$ values for each activity group were examined using separate between subjects one-way ANOVAs with LSD pairwise comparisons when appropriate. Separate stepwise multiple regression analyses were used to determine the relationships among selected predictor variables (% fat, LBM, and LTM) and $CP_{4.5\%}$, and $AWC_{4.5\%}$. Test-retest reliability of the total thigh lean mass measure was calculated using the intraclass correlation coefficient (ICC) model 3,1 (28). An Alpha level of $P \leq 0.05$ was considered statistically significant for all statistical analyses. All statistical analyses were performed with Statistical Package for the Social Sciences software (v.23.0 IBM SPSS Inc., Chicago, Illinois, USA).

CHAPTER IV: ANALYSIS OF DATA

Results

The descriptive characteristics of the subjects ($n=21$) within each training group ($n=7$; REC, SPORT, and END) are presented in Table 1. Table 2 displays individual subject values for CP_{ACT} , $CP_{4.5\%}$, AWC_{ACT} , and $AWC_{4.5\%}$ as well as the mean (\pm SD) for the groups.

Recreationally Trained Group

The results from the paired sample t-tests indicated there was no significant difference between $CP_{3\%}$ (169.86 ± 34.22 W) and $CP_{4.5\%}$ (172.86 ± 40.09 W), but a significant difference between $AWC_{3\%}$ (6.21 ± 2.87 kJ) and $AWC_{4.5\%}$ (10.29 ± 4.07 kJ). The 95% LOA for the $CP_{4.5\%}$ and $CP_{3\%}$ estimates ranged from -21.4 to 27.4 W. There was no significant relationship between the mean difference ($CP_{4.5\%} - CP_{3\%}$) and the mean of the two methods, and all subjects fell within ± 1.96 SD of the mean difference (Figure 4). The 95% LOA for the $AWC_{4.5\%}$ and $AWC_{3\%}$ estimates ranged from 0.58 to 7.56 kJ. There was a significant positive correlation ($r = 0.47$) between the mean difference ($AWC_{4.5\%} - AWC_{3\%}$) and the mean of the two methods, and all subjects fell within ± 1.96 SD of the mean difference (Figure 5). Table 3 displays the threshold values for the recreationally trained group.

The results of the one-way repeated measures ANOVA for the fatigue thresholds ($CP_{4.5\%}$, $CP_{3\%}$, GET, and RCP) indicate there were significant differences among the power outputs ($F = 14.49$, $p = 0.004$, partial $\eta^2 = 0.707$). The follow-up pairwise comparisons indicated the power output at the GET (107.85 ± 26.57 W) was significantly less than $CP_{3\%}$ (169.86 ± 34.22 W), $CP_{4.5\%}$ (172.86 ± 40.10 W), and the RCP ($176.12 \pm$

30.70 W). There were, however, no significant differences among power outputs for CP_{3%}, CP_{4.5%}, and RCP.

Table 4 displays the zero order correlation matrix for CP_{4.5%}, CP_{3%}, GET, RCP, AWC_{4.5%}, and AWC_{3%}. There were significant correlations between CP_{3%} and CP_{4.5%} ($r = 0.956$); RCP was significantly correlated with CP_{3%} ($r = 0.850$) and CP_{4.5%} ($r = 0.915$); and AWC_{3%} and AWC_{4.5%} were significantly correlated ($r = 0.925$). The GET was not significantly correlated with any of the CP test parameters or RCP.

Sport Group

The results from the paired sample t-tests indicated there were no significant differences between CP_{4%} (179.14 ± 44.79 W) and CP_{4.5%} (183.14 ± 46.73 W) or between AWC_{4%} (8.49 ± 3.65 kJ) and AWC_{4.5%} (8.72 ± 4.59 kJ). The 95% LOA for the CP_{4.5%} and CP_{4%} estimates ranged from -40.71 to 48.71 W. There was no significant relationship between the mean difference (CP_{4.5%} - CP_{4%}) and the mean of the two methods, and all subjects fell within ± 1.96 SD of the mean difference (Figure 6). The 95% LOA for the AWC_{4.5%} and AWC_{3%} estimates ranged from -4.52 to 4.99 kJ. There was no significant relationship between the mean difference (AWC_{4.5%} - AWC_{4%}) and the mean of the two methods, and all subjects fell within ± 1.96 SD of the mean difference (Figure 7).

Table 5 displays the threshold values for the SPORT group. The results of the one-way repeated measures ANOVA for the fatigue thresholds indicated there were significant differences among the power outputs ($F = 46.75$, $p < 0.001$, partial $\eta^2 = 0.886$). The follow-up pairwise comparisons indicated the power outputs for CP_{4.5%} (183.14 ± 46.73 W) and CP_{4%} (179.14 ± 44.79 W) were significantly greater than the power outputs

at the GET (107.98 ± 29.17 W) and the RCP (170.38 ± 40.91 W). The power output for the GET was significantly less than CP_{4.5%}, CP_{4%}, and RCP.

Table 6 displays the zero order correlation matrix for CP_{4.5%}, CP_{4%}, GET, RCP, AWC_{4.5%}, and AWC_{4%}. There were significant correlations ($P < 0.05$) between all variables except AWC_{4.5%} and CP_{4%} ($r = 0.701$, $P > 0.05$) and AWC_{4.5%} and GET ($r = 0.591$, $P > 0.05$).

Endurance Group

The results from the paired sample t-tests indicated there were no significant differences between CP_{5%} (188.86 ± 38.82 W) and CP_{4.5%} (187.57 ± 27.99 W) or between AWC_{5%} (10.11 ± 3.82 kJ) and AWC_{4.5%} (9.02 ± 3.07 kJ). The 95% LOA for the CP_{4.5%} and CP_{4%} estimates ranged from -32.66 to 30.09 W. There was no significant relationship between the mean difference (CP_{4.5%} - CP_{4%}) and the mean of the two methods, and all subjects fell within ± 1.96 SD of the mean difference (Figure 8). The 95% LOA for the AWC_{4.5%} estimates and the AWC_{3%} estimates ranged from -4.36 to 2.17 kJ. There was no significant relationship between the mean difference (AWC_{4.5%} - AWC_{4%}) and the mean of the two methods, and all subjects fell within ± 1.96 SD of the mean difference (Figure 9).

Table 7 displays the threshold values for the END trained group. The results of the one-way repeated measures ANOVA for the fatigue thresholds indicated there were significant differences among the power outputs ($F = 91.74$, $p < 0.001$, partial $\eta^2 = 0.939$). The follow-up pairwise comparisons indicated the power output at the GET (134.06 ± 67.51 W) was significantly less than CP_{5%} (188.86 ± 38.82 W), CP_{4.5%} (187.57 ± 27.99

W), and the power output at the RCP (198.52 ± 69.35 W). There were, however, no significant differences among power outputs for CP_{5%}, CP_{4.5%}, and RCP.

Table 8 displays the zero order correlation matrix for CP_{4.5%}, CP_{5%}, GET, RCP, AWC_{4.5%}, and AWC_{5%}. There were significant correlations between CP_{4.5%} and CP_{5%} ($r = 0.936$), CP_{4.5%} and GET ($r = 0.792$), CP_{4.5%} and RCP ($r = 0.888$), CP_{5%} and GET ($r = 0.823$), CP_{5%} and RCP ($r = 0.964$), and GET and AWC_{5%} ($r = 0.773$).

Training Group Comparisons

$\dot{V}O_2$ peak, GET, Peak Power during the CP_{4.5%}, Body Mass, % Fat, and CP_{4.5%}

The between subjects one-way ANOVA for $\dot{V}O_2$ peak indicated a mean difference ($F = 3.83$, $p = 0.41$) in $\dot{V}O_2$ peak values among the three groups (REC, SPORT, and END). The follow up pairwise comparisons indicated the $\dot{V}O_2$ peak for the END group ($\dot{V}O_2$ peak = 57.54 ± 9.57 , $p = 0.038$) was significantly greater than the $\dot{V}O_2$ peak for both the REC ($\dot{V}O_2$ peak = 46.64 ± 6.17 , $p = 0.038$) and SPORT ($\dot{V}O_2$ peak = 45.20 ± 10.96 , $p = 0.021$) groups. There were, however, no mean differences ($p = 0.771$) in the $\dot{V}O_2$ peak values between the REC and SPORT groups. The between subjects one-way ANOVA for the GET indicated no mean difference ($F = 2.371$, $p = 0.122$) in the GET values among the three groups (REC, SPORT, END).

The between subjects one-way ANOVA for peak power during the CP_{4.5%} test indicated no mean difference ($F = 0.206$, $p = 0.815$) among the three groups. The between subjects one-way ANOVA for body mass indicated no mean difference ($F = 1.489$, $p = 0.252$) among the three groups. The between subjects one-way ANOVA for % fat indicated a mean difference ($F = 4.110$, $p = 0.034$) in % fat among the three groups. The follow up pairwise comparisons indicated the % fat for the END group (% fat =

15.69 ± 10.59, p = 0.010) was lower than the SPORT group (% fat = 31.46 ± 13.35, p = 0.010). There were, however, no mean differences between the REC and SPORT groups (p = 0.175), and REC and END group (p = 0.163). The between subjects one-way ANOVA for CP_{4.5%} indicated no mean difference (F = 0.262, p = 0.773) among the three groups. The stepwise regression analyses indicated that only mineral-free lean body mass (LBM) contributed significantly to the prediction of AWC (AWC = 0.258[LBM] – 4.112 [r² = 0.709; SEE = 2.114 kJ; p < 0.001]) and only mineral-free lean thigh mass (LTM) contributed significantly to the prediction of CP (CP = 9.596[LTM] – 74.456 [r² = 0.608; SEE = 24.153 W; p < 0.001]). Test-retest reliability using the intraclass correlation coefficient (ICC) 3, 1 for estimating total thigh lean mass resulted in an ICC_{3,1} of 0.998. Correlations among the parameters of the CP test and body composition characteristics are presented in Table 9. Results from the zero order correlation matrix indicate there was a significant correlation between AWC_{4.5%} and mineral-free lean thigh mass (LTM) (r = 0.825) as well as AWC_{4.5%} and mineral-free lean body mass (r = 0.842).

Discussion

Recreationally Trained Group

The mean (±SD) $\dot{V}O_2$ peak (46.6 ± 6.2 ml·kg⁻¹·min⁻¹; males = 46.7 ± 9.6 ml·kg⁻¹·min⁻¹; females = 46.6 ± 3.8 ml·kg⁻¹·min⁻¹) for the REC group in the present study was comparable to the mean $\dot{V}O_2$ peak values (43.0 ± 7.4 ml·kg⁻¹·min⁻¹) previously reported for recreationally trained subjects (2). The mean $\dot{V}O_2$ peak values for the males and females in the REC group resulted in classification of “good“ and “excellent“, respectively (23). The maximal power output from the incremental test to exhaustion (225.7 ± 47.2 W) and the GET (31.9 ± 12.8 mL·kg⁻¹·min⁻¹), were consistent

with the maximal power output (225 ± 58 W) and the GET (30.73 ± 4.02 mL·kg⁻¹·min⁻¹) values previously reported (2). The GET occurred at $54 \pm 10\%$ of $\dot{V}O_2$ peak, and was within the range of GET values previously reported (54 – 75% $\dot{V}O_2$ peak) for recreationally trained individuals (2). Thus, the $\dot{V}O_2$ peak, maximal power output, and GET values for the REC subjects in this present study were consistent with recreationally trained subjects (2, 4).

In this present study, the CP_{4.5%} and CP_{3%} tests resulted in patterns of responses (Figure 10 and 11) for the power output versus time relationships that were consistent with the patterns of response previously reported (2) for the CP_{3min} test with the resistance set at 4.5% of body weight. The patterns for power output versus time relationships for the CP_{3%} and CP_{4.5%} displayed initial increases in power output during the first 5 to 10 seconds, followed by steep declines during the first two minutes of the tests. The final minute of the tests resulted in gradual decreases and plateaued during the final 30 seconds. A qualitative analysis of the two figures (Figure 10 and 11) demonstrated a lower initial power output and more rapid initial decline in power output for the CP_{3%} test (Figure 10) compared to the CP_{4.5%} test. The subjects reported post-CP_{3%} that the resistance felt too light and resulted in a sensation of their momentum or inertia getting ahead of them causing them to slow their cadence to allow the resistance to catch up. The patterns of responses for the CP_{4.5%} (Figure 11) resulted in a greater initial power output and more gradual decline in power output, which was more consistent with the responses reported in previous studies (2, 9, 26). Thus, the results of the present study indicated the CP_{4.5%} test resulted in a pattern of response for the power output versus time

relationship that was more consistent with the patterns previously reported (2, 9, 26), than the CP_{3%} test.

We hypothesized that the resistance setting on the cycle ergometer would have no effect on CP and AWC estimates in the REC group. The current findings indicated there was no mean difference between CP_{3%} (169.86 ± 34.22 W) and CP_{4.5%} (172.86 ± 40.09 W), but a significant difference between AWC_{3%} (6.21 ± 2.87 kJ) and AWC_{4.5%} (10.29 ± 4.07 kJ) (Table 3). The mean CP_{3%} and CP_{4.5%} for the REC group in the present study were similar to the mean CP (186 ± 44 W) previously reported (2) from the CP_{3min} test in recreationally trained subjects. The Bland Altman plot for the analysis of agreement between the CP_{4.5%} test and CP_{3%} test revealed there was no systematic bias for the CP estimates (Figure 4). These findings supported our hypothesis, and indicated that the resistance setting (3% or 4.5%) had no significant effect on the estimates of CP_{3min} test. The AWC_{4.5%} for the REC group in the present study was similar to the mean AWC (9.84 ± 4.39 kJ) previously reported (2) from the CP_{4.5%} test in recreationally trained subjects. The mean AWC_{3%}, however, was not consistent with the mean AWC values (9.84 ± 4.39 kJ and 10.4 ± 2.6 kJ) of recreationally trained subjects that have been previously reported (2, 4). The Bland Altman plot for the analysis of agreement between AWC_{4.5%} and AWC_{3%} (Figure 5) revealed a systematic bias between AWC estimates. In addition, there was a significant relationship between the mean differences (AWC_{4.5%} - AWC_{3%}) and the mean of the two values, indicating that the difference between the AWC_{4.5%} and AWC_{3%} was greater for higher AWC values. Thus, the current findings did not support our hypothesis and indicated that the resistance set at 3% of body weight resulted in an estimate of AWC that was significantly less than the AWC with the resistance set at

4.5%. These findings suggested that a resistance set at 3% of body weight for the CP_{3min} test may be too low to accurately estimate both CP and AWC. Therefore, the current findings indicated that using a resistance of 4.5% of body weight in recreationally trained subjects resulted in more accurate estimates of both CP and AWC, than using a resistance of 3%, when compared the parameters of the CP tests previously reported (2, 9, 26).

There were no significant differences among CP_{4.5%} (173 ± 40 W), CP_{3%} (170 ± 27 W), and the power output associated with RCP (176 ± 31 W) for the REC group, and they were significantly correlated ($r = 0.85 - 0.92$) (Tables 3 and 4). The power output at the GET (108 ± 27 W) was significantly less than both CP and RCP. Previous studies (3, 24) have suggested that the CP and RCP represent a similar intensity, that is greater than the GET, and demarcate the heavy from severe exercise-intensity domains. Thus, the current findings were consistent with the findings of others (3, 25), and indicated that the CP and RCP may reflect a similar exercise intensity.

Anaerobic Sport Trained Group

The mean (\pm SD) $\dot{V}O_2$ peak (45.2 ± 11.0 ml·kg⁻¹·min⁻¹; males = 49.5 ± 13.1 ml·kg⁻¹·min⁻¹; females = 39.4 ± 3.8 ml·kg⁻¹·min⁻¹) for the SPORT group in the present study was comparable to the mean $\dot{V}O_2$ peak values (51.2 ± 2.8 ml·kg⁻¹·min⁻¹) previously reported for club-level hockey and rugby male subjects (12). The mean $\dot{V}O_2$ peak values for the males and females in the SPORT group resulted in classification of “good“ and “fair“, respectively (23). The GET value (22.4 ± 4.1 mL·kg⁻¹·min⁻¹; males = 24.76 ± 3.26 mL·kg⁻¹·min⁻¹, females = 19.35 ± 3.20 mL·kg⁻¹·min⁻¹) were lower than the GET (32.37 ± 7.37 mL·kg⁻¹·min⁻¹) previously reported (12) in male subjects only (12). The GET occurred at $50 \pm 16\%$ of $\dot{V}O_2$ peak, and was lower than the range of GET

values previously reported (63 – 77% $\dot{V}O_2$ peak) for club-level hockey and rugby trained individuals (12). Thus, the $\dot{V}O_2$ peak and GET values for the SPORT subjects in this present study were not consistent with club-level anaerobic sport trained subjects (12). The lower $\dot{V}O_2$ peak and GET values in the current study, when compared to other samples of club-level anaerobic sport trained subjects (12), may be related to the training status of the SPORT subjects. Three of the seven SPORT subjects were club soccer players who were at the end of the four month off-season in which they did not have a structured training program. Thus, the decrease in training volume for 43% of the subjects in the SPORT group may account for the lower $\dot{V}O_2$ peak values and aerobic parameters in the current sample, when compared to other aerobic and anaerobic sport athletes (12).

In this present study, the CP_{4.5%} and CP_{4%} tests resulted in patterns of responses (Figure 12 and 13) for the power output versus time relationships that were consistent with the patterns of response for the CP_{3min} test with the resistance set at 4.5% of body weight, previously reported (2). The patterns for power output versus time relationships for the CP_{4%} and CP_{4.5%} displayed initial increases in power output during the first 5 to 10 seconds, followed by steep declines during the first two minutes of the tests. The final minute of the tests resulted in gradual decreases and plateaued during the final 30 seconds. A qualitative analysis of the two figures (Figure 12 and 13) demonstrated a similar initial power output, but an earlier plateau for the CP_{4%} test (Figure 13) compared to the CP_{4.5%} test. The power output plateaued at approximately 60 seconds for the CP_{4%} test (Figure 13). The CP_{4.5%} (Figure 12) test resulted in a more gradual decline in the power output than the CP_{4%} (Figure 13), and the plateau occurred after approximately

120 to 140 seconds. The power output versus time responses for the CP_{4.5%} test, were consistent with the responses reported in previous studies (2, 9, 26) that indicated a plateau at approximately 120 to 150 seconds of the test. Thus, the results of the present study indicated the CP_{4.5%} test resulted in a pattern of response for the power output versus time relationship that was more consistent with the patterns previously reported (2, 9, 26), than the CP_{4%} test.

We hypothesized that the resistance setting on the cycle ergometer would have no effect on CP and AWC estimates in the SPORT group. The current findings indicated there were no mean differences between CP_{4%} (179.14 ± 44.79 W) and CP_{4.5%} (183.14 ± 46.73 W) or between AWC_{4%} (8.49 ± 3.65 kJ) and AWC_{4.5%} (8.72 ± 4.59 kJ) (Table 5). The Bland Altman plot for the analysis of agreement between the CP_{4.5%} test and CP_{4%} test revealed there was no systematic bias for the CP estimates (Figure 6). These findings supported our hypothesis, and indicated that the resistance setting (4% or 4.5%) had no significant effect on the estimates of CP from the 3-min all-out test. The Bland Altman plot for the analysis of agreement between AWC_{4.5%} and AWC_{3%} (Figure 7) revealed there was no systematic bias between AWC estimates. Thus, the current findings supported our hypothesis and indicated that the resistance set at 4% of body weight resulted in an estimate of AWC that was not significantly different from the AWC estimated from the CP_{3min} test with the resistance set at 4.5%. Therefore, the results of the present study indicated that the resistance set at 4% or 4.5% of body weight had no effect on the parameter estimates of the CP_{3-min} test in aerobic and anaerobic sport athletes.

The CP_{4.5%} (183 ± 47 W) and CP_{4%} (179 ± 45 W) were greater than the power output associated with RCP (170 ± 41 W) for the SPORT group, and all power outputs,

were significantly correlated ($r = 0.95 - 0.96$) (Table 6). The power output at the GET (108 ± 29 W) was significantly less than both CP and RCP. The significant difference between the CP and RCP was not consistent with previous studies (3, 25) that have suggested the CP and RCP represent a similar exercise intensity, and demarcate the heavy from severe exercise intensity domains. It is possible that the CP values in the present study overestimated the highest power output associated with steady state metabolic responses and the demarcation of the heavy and severe intensity domains. Future studies should examine the metabolic responses and sustainability of the CP estimates derived from the CP_{3min} test in aerobic and anaerobic sport subjects.

Endurance Group

The mean (\pm SD) $\dot{V}O_2$ peak (57.5 ± 9.6 ml·kg⁻¹·min⁻¹; males = 62.3 ± 9.3 ml·kg⁻¹·min⁻¹; females = 51.3 ± 36.4 ml·kg⁻¹·min⁻¹) for the END group in the present study was comparable to the mean $\dot{V}O_2$ peak values (54.9 ± 3.2 ml·kg⁻¹·min⁻¹) previously reported for endurance trained subjects (26). Elite trained endurance runners, however, typically reach higher mean $\dot{V}O_2$ peak values (72.1 ± 3.1 ml·kg⁻¹·min⁻¹) (7), indicating that the END subjects in this present study were not elite trained endurance runners. The mean $\dot{V}O_2$ peak values for both the males and females in the END group resulted in classifications of “superior“(23). The GET value (2.1 ± 0.9 L·min⁻¹) occurred at $54.0 \pm 12.4\%$ of the $\dot{V}O_2$ peak, which was lower than typically recorded ($\sim 80\%$ of the $\dot{V}O_2$ peak) in elite endurance athletes (7), but within the range of those values recorded in endurance trained college-aged students (26). Thus, the $\dot{V}O_2$ peak and GET values for the

END subjects in this present study were consistent with endurance trained college-aged students, but not elite endurance trained athletes (26, 7).

In this present study, the CP_{4.5%} and CP_{5%} tests resulted in patterns of responses (Figure 14 and 15) for the power output versus time relationships that were consistent with the patterns of response for the CP_{3min} test with the resistance set at 4.5% of body weight, previously reported (2). The patterns for power output versus time relationships for the CP_{5%} and CP_{4.5%} displayed initial increases in power output during the first 5 to 10 seconds, followed by steep declines during the first two minutes of the tests. The final minute of the tests resulted in gradual decreases and plateaued during the final 30 seconds. A qualitative analysis of the two figures (Figure 14 and 15) demonstrated similar initial power outputs, gradual plateaus, and overall profiles. The plateaus for the CP_{5%} and CP_{4.5%} tests (Figure 14 and 15) appeared to occur around the final 30 seconds in both. Thus, the results of the present study indicated the CP_{5%} and CP_{4.5%} tests resulted in a pattern of responses for the power output versus time relationship that were consistent with the patterns previously reported (2, 9, 26).

We hypothesized that the resistance setting on the cycle ergometer would have no effect on CP and AWC estimates in the END group. The current findings indicated there were no mean differences between CP_{5%} (188.86 ± 38.82 W) and CP_{4.5%} (187.57 ± 27.99 W) or between AWC_{5%} (10.11 ± 3.81 kJ) and AWC_{4.5%} (9.02 ± 3.07 kJ) (Table 7). The Bland Altman plot for the analysis of agreement between the CP_{4.5%} test and CP_{5%} test revealed there was no systematic bias for the CP estimates (Figure 8). These findings supported our hypothesis, and indicated that the resistance setting (5% or 4.5%) had no significant effect on the estimates of CP_{3min} test. The AWC_{4.5%} and AWC_{5%} for the END

group in the present study was slightly less than the AWC (17.4 ± 5.8 kJ) reported for elite endurance athletes (7). The Bland Altman plot for the analysis of agreement between AWC_{4.5%} and AWC_{5%} (Figure 9) revealed there was no systematic bias between AWC estimates. Thus, the current findings supported our hypothesis and indicated that the resistance set at 5% of body weight resulted in an estimate of AWC that was not significantly different than the AWC with the resistance set at 4.5%. Therefore, the results of the present study indicated that the resistance set at 4.5% or 5% of body weight had no effect on the parameter estimates of the CP_{3-min} test in endurance-trained subjects.

There were no significant differences among the CP_{4.5%} (188 ± 28 W), CP_{5%} (188.86 ± 38.82 W), and the power output associated with the RCP (198 ± 69 W) for the END group, and all power outputs were significantly correlated ($r = 0.82 - 0.96$) (Tables 7 and 8). The power output at the GET (134 ± 67 W) was significantly less than both estimates of CP and the RCP. The current findings were consistent with those of previous studies (3, 24) that have indicated the CP and RCP are greater than the GET and represent a similar exercise intensity.

Training Group Comparisons

The aerobic capacity of the END group ($\dot{V}O_2 \text{ peak} = 57.5 \pm 9.6$ ml·kg⁻¹·min⁻¹) was significantly greater than the capacity of the REC ($\dot{V}O_2 \text{ peak} = 46.6 \pm 6.2$ ml·kg⁻¹·min⁻¹) and SPORT ($\dot{V}O_2 \text{ peak} = 45.2 \pm 11.0$ ml·kg⁻¹·min⁻¹) groups. There were, however, no significant differences among the GET values for the three training groups. Thus, in the present study, the aerobic capacity of the END group was greater than both REC and SPORT groups, but the training groups had similar fatigue thresholds.

There were no significant differences in the CP_{4.5%} estimated among the three training groups and the patterns of responses for all groups were very similar. Specifically, the percent decline in power output during the 3-min all-out test was comparable among the three groups (REC = 63%, SPORT = 66%, END = 65%). The REC group 5-second average peak power (481 ± 190 W) was slightly lower, but not significantly different from both the SPORT (535 ± 144 W) and END (521 ± 150 W) groups. Typically, SPORT and END trained subjects attain higher peak power values (11, 12), which is reflective of the implementation of sport-specific strength and conditioning training to maximize athletic performance and the ability to produce power during competition (12). The non-significant differences among the CP_{4.5%} and peak power values was related to the small sample sizes ($n=7$), resulting in the low statistical power for the between group comparisons.

The correlations among body composition characteristics and CP_{4.5%} test parameters (CP_{4.5%} and AWC_{4.5%}) for the REC (Table 4), SPORT (Table 6), and END (Table 8) were highly correlated with LBM and LTM. No previous studies have examined the contribution of body composition characteristics to the parameters of the CP test. The stepwise regression analyses indicated that only lean body mass (LBM) contributed significantly to the prediction of AWC_{4.5%}, while only lean thigh mass (LTM) contributed significantly to the prediction of CP_{4.5%}. Practical implications for improving AWC and CP would include resistance-training programs designed to increase total body and thigh lean mass, respectively.

Limitations and Future Directions

This study examined the CP and AWC estimates derived from the CP 3-min all-out test with the resistance set at 4.5% of body weight as recommended by Bergstrom et al. (2) or with the resistance set based on the activity level of the subjects as suggested by Clark et al. (10). There were several limitations, however, to this study. Although the primary purpose of this study was to examine the effect of the resistance setting within the each group, between group comparisons were of interest for differentiating the training statuses among groups. The small sample size in each group (n=7), however, resulted in low statistical power and did not allow for accurate between group comparisons. Future studies should examine the effect of the interaction between the resistance setting and training status of the subject on the CP 3-min all-out test parameters using a mixed model approach. This would include having 12-15 subjects within each group, and all subjects completing each the CP 3-min all-out test at each of the three activity level resistance settings (3%, 4%, and 5%).

Another limitations of this study was that the SPORT group was not as highly trained as was expected. Almost half of the SPORT group was just ending their off-season (3-4 months), which did not include any formal off-season training resulting in little to no difference in aerobic fitness level when compared to the REC group. Future studies should examine a group of aerobic and anaerobic sport athletes during a period of greater training volume. In addition, none of the subjects in this study were elite athletes. It is possible that a higher resistance setting for the CP_{3min} test would be necessary for elite aerobic athletes, similar to the Wingate Anaerobic Test (WAT). The WAT utilizes a simplified protocol of 7.5% body mass resistance, but previous studies (11) have recommended a setting of 8.5% for highly trained, male, power athletes. Thus, it is

possible that elite aerobic athletes would require a higher resistance setting for the CP_{3min} test to accurately estimate the CP and AWC parameters.

Conclusions

In conclusion, the purpose of this study was to determine if the CP and AWC estimates from a single 3-minute all-out test were affected by the percentage of body weight used to set the resistance on a Monark cycle ergometer. For the REC group, the CP estimates were not affected by the resistance setting; however, the AWC_{3%} values were significantly lower than the AWC_{4.5%} values and not consistent with AWC values previously reported (2) in REC subjects. These findings indicated that using a resistance of 4.5% of body weight in REC subjects resulted in more accurate estimates of both CP and AWC, than using a resistance of 3%, when compared the parameters of the CP tests previously reported (2, 9, 26). The resistance based on the activity level (4% for SPORT or 5% for END) or 4.5% of body weight had no effect on the parameter estimates of the CP_{3-min} test in the SPORT or END group. Therefore, the principal finding of this study was that a resistance of 4.5% of body weight for CP_{3min} test may be used to estimate CP and AWC, without regard to the training status of the subjects. These findings support the use of a common percentage of body weight to set the resistance (4.5% of body weight) for the CP_{3min} test protocol in REC, SPORT, and END trained subjects.

Table 1. Mean \pm Standard Deviation for subject demographics for recreationally trained group, sport group, and endurance trained group.

Group	Age (years)	Height (cm)	Body Composition		Total Lean Body Mass (kg)	R+L Thigh Lean Mass (kg)	$\dot{V}O_2$ Peak (ml·kg·min ⁻¹)
			Body Mass (kg)	% Fat			
Recreational Trained (n = 7)	22.0 \pm 2.4	171.7 \pm 9.3	73.1 \pm 22.1	23.7 \pm 5.2	53.3 \pm 16.6	11.12 \pm 4.18	46.6 \pm 6.2
Sport (n = 7)	22.3 \pm 2.5	169.6 \pm 9.6	80.9 \pm 21.3	31.5 \pm 13.3 ⁺	52.2 \pm 13.6	11.54 \pm 3.11	45.2 \pm 11.0
Endurance Trained (n = 7)	23.5 \pm 2.6	173.7 \pm 5.2	64.0 \pm 8.4	15.7 \pm 10.6	50.7 \pm 7.3	10.66 \pm 1.88	57.5 \pm 9.6*

* significantly greater (P < 0.05) than the recreationally and sport trained groups

⁺ significantly greater (P < 0.05) than the endurance trained group

Table 2. Individual subject values (Subj) from the 3-min all-out critical power (CP_{3min}) test (critical power [CP] and anaerobic work capacity [AWC]) with the resistance set at 3%, 4%, 5%, or 4.5% of body weight from each group (REC = recreationally trained, SPORT = anaerobic sport, END = endurance trained) and gender (G) with each group mean ± standard deviation values.

Subj	G	REC				Subj	G	SPORT				Subj	G	END			
		CP ₃ %	CP ₄ 5%	AWC ₃ %*	AWC ₄ .5%			CP ₄ %	CP ₄ 5%	AWC 4%	AWC ₄ .5%			CP ₅ %	CP ₄ 5%	AWC 3%	AWC ₄ .5%
1	F	133	125	4.1	9.8	1	F	147	142	3.5	3.8	1	F	157	160	4.5	5.1
2	F	158	154	5.9	9.9	2	F	148	129	5.6	8.7	2	M	147	157	7.4	7.1
3	M	209	213	11.9	18.0	3	M	165	158	7.2	7.1	3	F	218	208	7.2	8.0
4	M	147	161	6.9	10.1	4	M	195	224	10.2	11.6	4	F	172	165	12.2	10.2
5	M	220	241	6.0	11.6	5	F	128	158	7.4	3.2	5	M	180	201	11.1	7.2
6	F	181	167	6.2	8.3	6	M	218	241	11.7	10.7	6	M	260	231	14.7	14.0
7	F	141	149	2.7	4.5	7	M	253	230	14.0	16.2	7	M	188	191	13.8	11.7
MEAN		170	173	6.2	10.3			179	183	8.5	8.7			189	188	10.1	9.0
SD		34	40	2.9	4.1			45	47	3.7	4.6			39	28	3.8	3.1

*significant difference (P < 0.05) between the 3% and 4.5% resistance setting.

TABLE 3. Threshold values among parameters of the 3-min all-out critical power (CP_{3min}) test (critical power [CP]) with the resistance set at 4.5% and 3% of body weight, gas exchange threshold (GET), and respiratory compensation point (RCP) for the recreationally trained group (n=7).

	Rec Group			
	CP 3%	CP 4.5%	GET*	RCP
	W	W	W	W
MEAN	169.86	172.86	107.85	176.12
STDEV	34.22	40.09	26.57	30.7

* GET significantly ($P < 0.05$) lower than CP 3%, CP 4.5%, and RCP.

Table 4. Correlations among parameters of the 3-min all-out critical power (CP_{3min}) test (critical power [CP] and anaerobic work capacity [AWC]) with the resistance set at 4.5% and 3% of body weight, gas exchange threshold (GET), and respiratory compensation point (RCP) for the recreationally trained group (n=7).

	CP 4.5%	CP 3%	GET	RCP	AWC 4.5%	AWC 3%
CP 4.5%	1.000					
CP 3%	0.956*	1.000				
GET	0.053	0.006	1.000			
RCP	0.915*	0.850*	0.195	1.000		
AWC 4.5%	0.594	0.646	0.018	0.282	1.000	
AWC 3%	0.577	0.643	0.370	0.370	0.925*	1.000

$CP_{4.5\%}$ and $AWC_{4.5\%}$ = parameters of the CP_{3min} test with the resistance set at 4.5% of body weight, $CP_{3\%}$ and $AWC_{3\%}$ = parameters of the CP_{3min} test with the resistance set at 3% of body weight

*significant at $p \leq 0.05$

TABLE 5. Threshold values among parameters of the 3-min all-out critical power (CP_{3min}) test (critical power [CP]) with the resistance set at 4.5% and 4% of body weight, gas exchange threshold (GET), and respiratory compensation point (RCP) for the sport trained group (n=7).

	Sport Group			
	CP 4%*	CP 4.5%*	GET†	RCP^x
	W	W	W	W
MEAN	179.14	183.14	107.98	170.38
STDEV	44.79	46.73	29.17	40.91

* CP 4% & CP 4.5% significantly different from GET and RCP.

† GET significantly different from CP 4%, CP 4.5%, and RCP.

^x RCP significantly different from CP 4.5% and GET.

*,†, ^x significant at $p \leq 0.05$

Table 6. Correlations among parameters of the 3-min all-out critical power (CP_{3min}) test (critical power [CP] and anaerobic work capacity [AWC] with the resistance set at 4.5% and 4% of body weight, gas exchange threshold (GET), and respiratory compensation point (RCP) for the sport trained group (n=7).

	CP 4.5%	CP 4%	GET	RCP	AWC 4.5%	AWC 4%
CP 4.5%	1.000					
CP 4%	0.877*	1.000				
GET	0.866*	0.944*	1.000			
RCP	0.961*	0.951*	0.947*	1.000		
AWC 4.5%	0.866*	0.701	0.591	0.818*	1.000	
AWC 4%	0.917*	0.902*	0.839*	0.951*	0.889*	1.000

$CP_{4.5\%}$ and $AWC_{4.5\%}$ = parameters of the CP_{3min} test with the resistance set at 4.5% of body weight, $CP_{4\%}$ and $AWC_{4\%}$ = parameters of the CP_{3min} test with the resistance set at 4% of body weight

*significant at $p \leq 0.05$

TABLE 7. Threshold values among parameters of the 3-min all-out critical power (CP_{3min}) test (critical power [CP]) with the resistance set at 4.5% and 5% of body weight, gas exchange threshold (GET), and respiratory compensation point (RCP) for the endurance trained group (n=7).

	Endurance Group			
	CP 5%	CP 4.5%	GET*	RCP
	W	W	W	W
MEAN	188.86	187.57	134.06	198.52
STDEV	38.82	27.99	67.51	69.35

* GET significantly ($P < 0.05$) lower than CP 5%, CP 4.5%, and RCP.

Table 8. Correlations among parameters of the 3-min all-out critical power (CP_{3min}) test (critical power [CP] and anaerobic work capacity [AWC] with the resistance set at 4.5% and 5% of body weight, gas exchange threshold (GET), and respiratory compensation point (RCP) for the endurance trained group (n=7).

	CP 4.5%	CP 5%	GET	RCP	AWC 4.5%	AWC 5%
CP 4.5%	1.000					
CP 5%	0.936*	1.000				
GET	0.792*	0.823*	1.000			
RCP	0.888*	0.964*	0.932	1.000		
AWC 4.5%	0.441	0.529	0.200	0.363	1.000	
AWC 5%	0.560	0.551	0.773*	0.699	0.091	1.000

$CP_{4.5\%}$ and $AWC_{4.5\%}$ = parameters of the CP_{3min} test with the resistance set at 4.5% of body weight, $CP_{5\%}$ and $AWC_{5\%}$ = parameters of the CP_{3min} test with the resistance set at 5% of body weight

*significant at $p \leq 0.05$

Table 9. Correlations among parameters of the critical power (CP) test and body composition characteristics (n=21).

	CP	% FAT	AWC	LEAN THIGH MASS	LEAN BODY MASS
CP 4.5%	1.000				
% FAT	-0.138	1.000			
AWC 4.5%	0.234	-0.069	1.000		
LEAN THIGH MASS	0.036	-0.073	0.825*	1.000	
LEAN BODY MASS	0.068	-0.188	0.842*	0.977	1.000

% fat = body fat percent, AWC = anaerobic work capacity, LTM = lean thigh mass, and LBM = lean body mass.

*r significant at $p \leq 0.05$

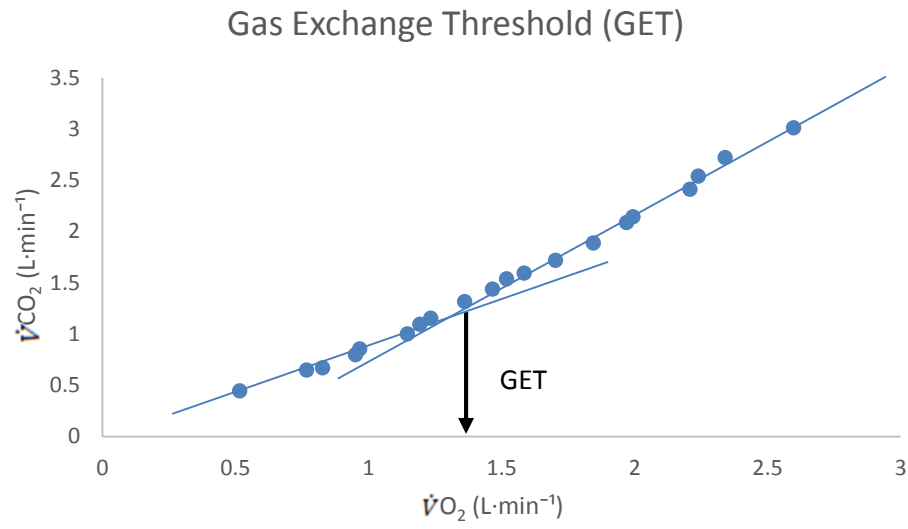


FIGURE 1. The method used for determining gas exchange threshold (GET).

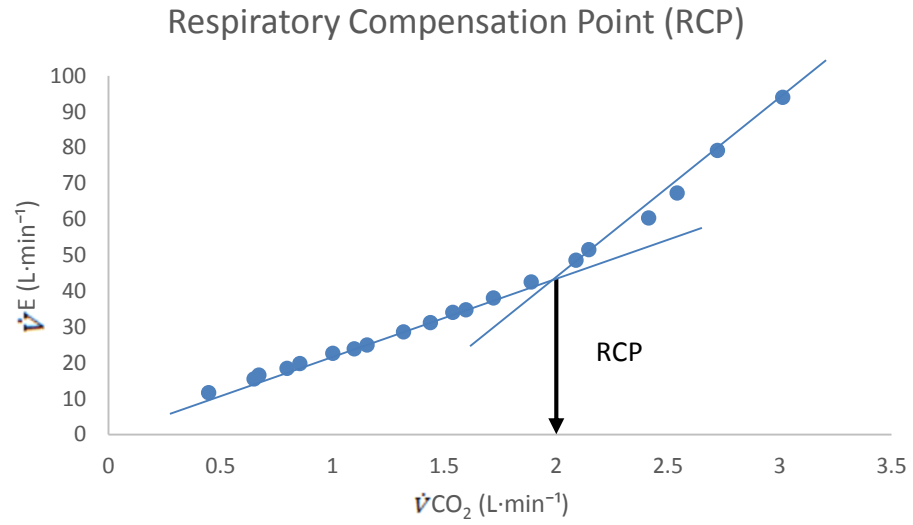


FIGURE 2. The method used for determining respiratory compensation point (RCP). The RCP was defined as the $\dot{V}O_2$ value corresponding to the $\dot{V}CO_2$ value at the breakpoint in the $\dot{V}E/\dot{V}CO_2$ relationship.

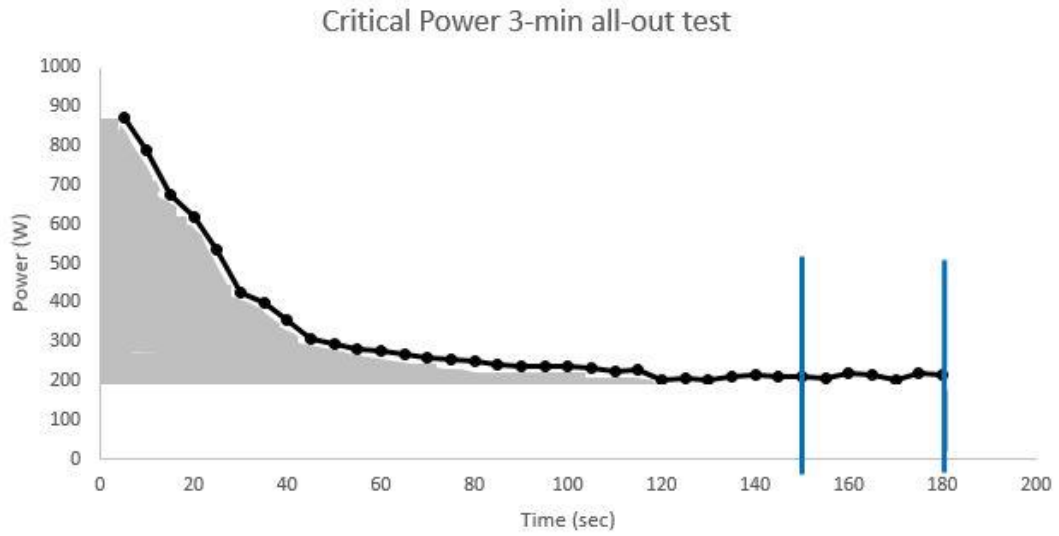


FIGURE 3. Model critical power (CP) graph. The gray area under the curve represents anaerobic work capacity (AWC) and was estimated from the equation $AWC = ([\text{mean power (MP)} (\text{average power during first 150 seconds}) - CP] \times 150) / 100$. The blue vertical lines represent CP which was the average power during the last 30 sec of the test.

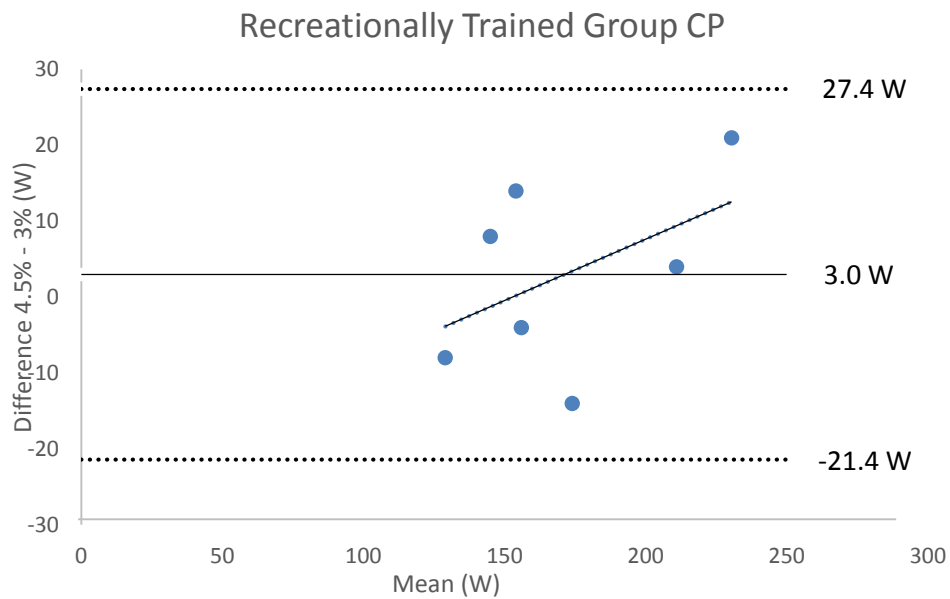


FIGURE 4. Bland Altman analysis of agreement between the critical power (CP) test with resistance set at 4.5% and 3% for the recreationally trained group. The middle solid line represents the mean of the difference between the CP estimates from the two methods. The upper and lower dotted lines represent the bias ± 1.96 SD (95% Limits of Agreement). The $r^2 = 0.23$.

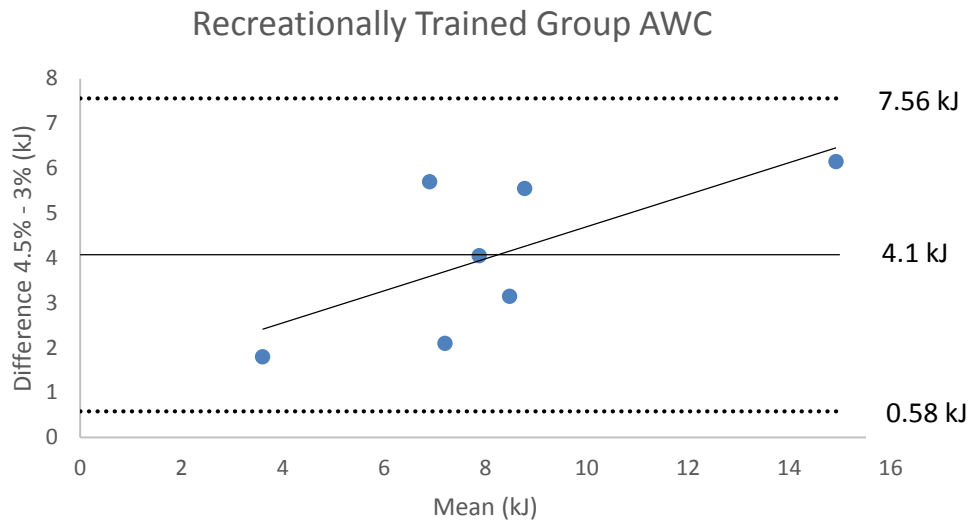


FIGURE 5 Bland Altman analysis of agreement between the critical power (CP) test with resistance set at 4.5% and 3% for the recreationally trained group. The middle solid line represents the mean of the difference between the CP estimates from the two methods. The upper and lower dotted lines represent the bias ± 1.96 SD (95% Limits of Agreement). The $r^2 = 0.47$.

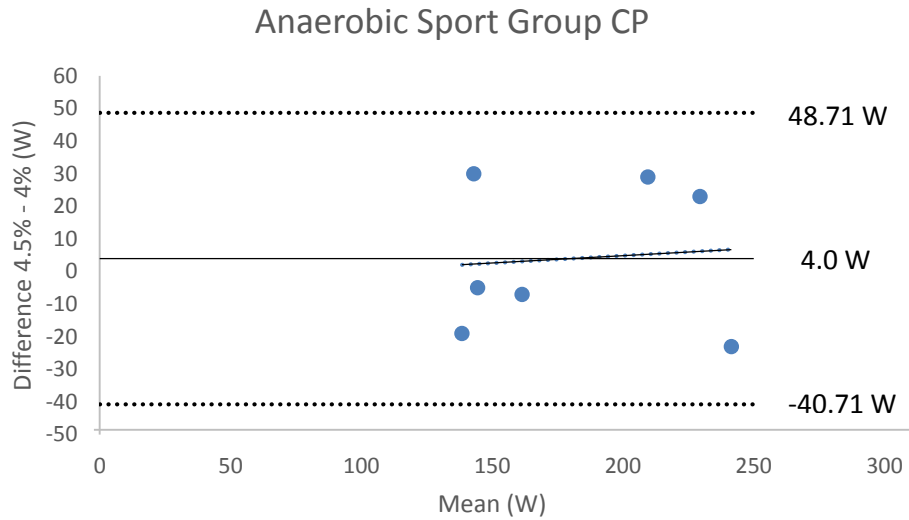


FIGURE 6 Bland Altman analysis of agreement between the critical power (CP) test with resistance set at 4.5% and 4% for the anaerobic sport trained group. The middle solid line represents the mean of the difference between the CP estimates from the two methods. The upper and lower dotted lines represent the bias ± 1.96 SD (95% Limits of Agreement). The $r^2 = 0.01$.

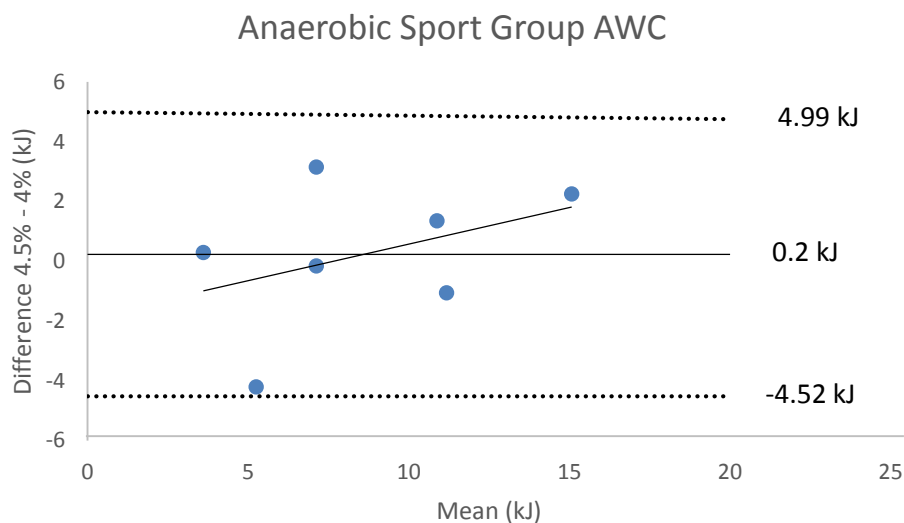


FIGURE 7. Bland Altman analysis of agreement between the critical power (CP) test with resistance set at 4.5% and 4% for the anaerobic sport trained group. The middle solid line represents the mean of the difference between the CP estimates from the two methods. The upper and lower dotted lines represent the bias ± 1.96 SD (95% Limits of Agreement). The $r^2 = 0.16$.

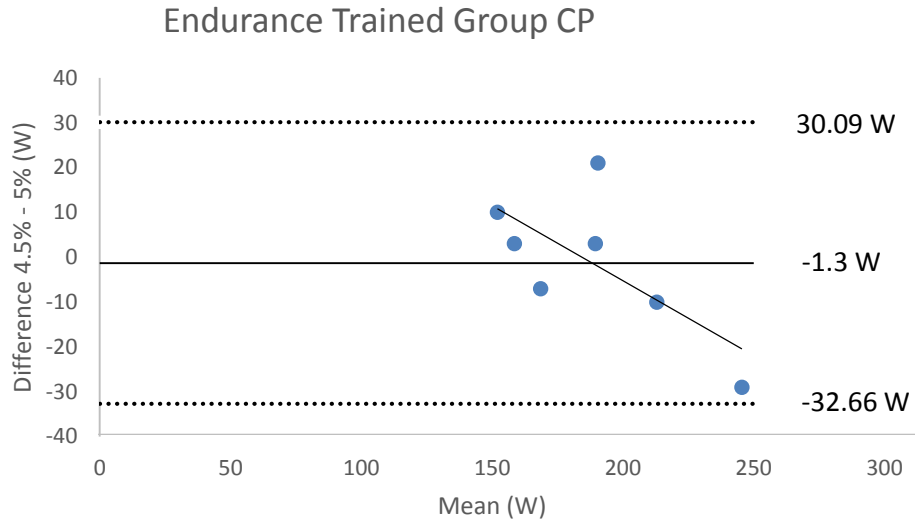


FIGURE 8. Bland Altman analysis of agreement between the critical power (CP) test with resistance set at 4.5% and 5% for the endurance trained group. The middle solid line represents the mean of the difference between the CP estimates from the two methods. The upper and lower dotted lines represent the bias ± 1.96 SD (95% Limits of Agreement). The $r^2 = 0.47$.

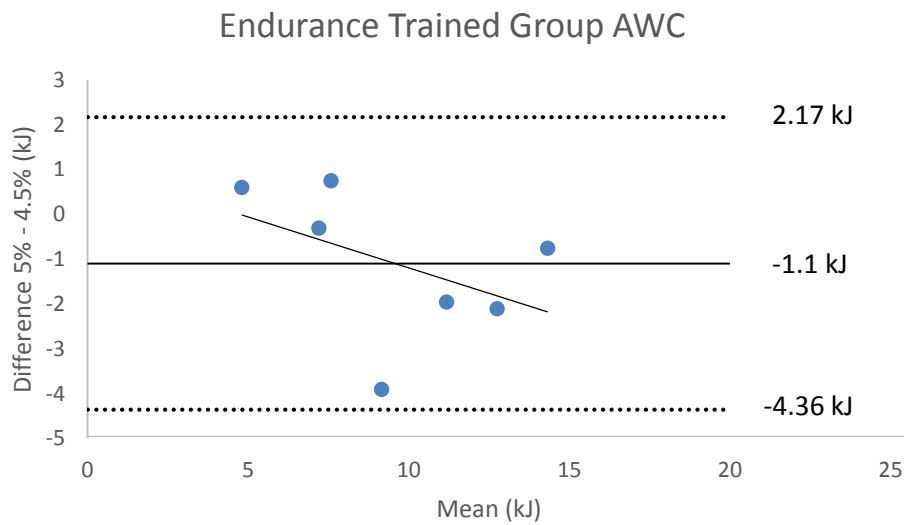


FIGURE 9 Bland Altman analysis of agreement between the critical power (CP) test with resistance set at 4.5% and 5% for the endurance trained group. The middle solid line represents the mean of the difference between the CP estimates from the two methods. The upper and lower dotted lines represent the bias ± 1.96 SD (95% Limits of Agreement). The $r^2 = 0.21$.

RECREATIONALLY TRAINED GROUP 4.5%

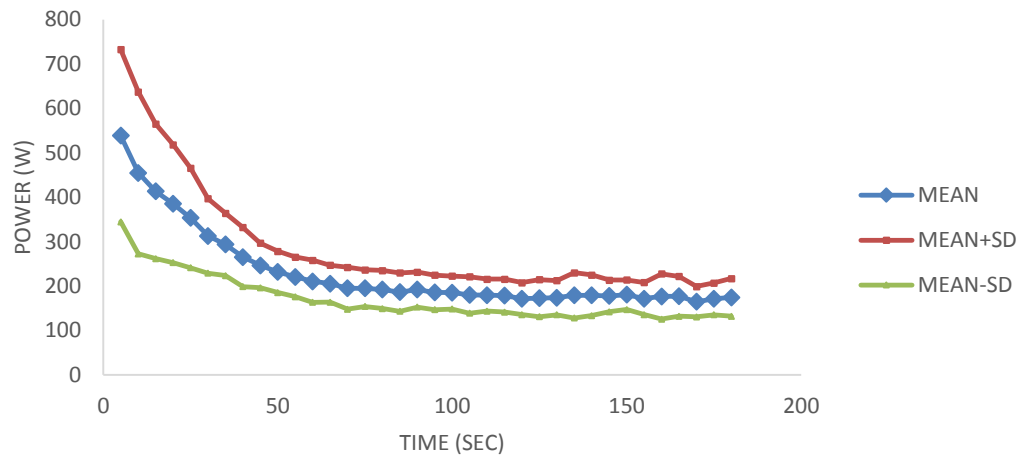


Figure 10. The mean \pm SD pattern of response for the critical power (CP) test with the resistance set at 4.5% body weight for the recreationally trained group. Middle line indicates the mean response with \pm standard deviation above and below the mean.

RECREATIONALLY TRAINED GROUP 3%

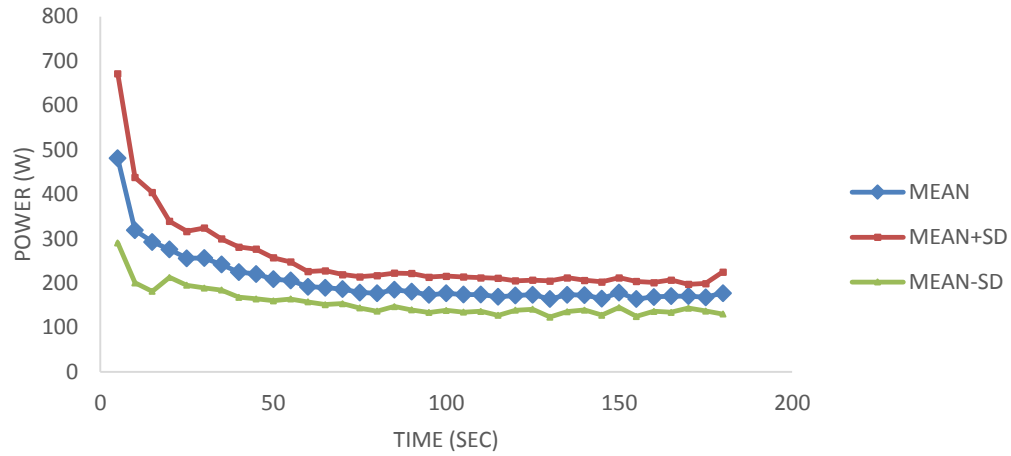


Figure 11. The mean \pm SD pattern of response for the critical power (CP) test with the resistance set at 3% body weight for the recreationally trained group. Middle line indicates the mean response with \pm standard deviation above and below the mean.

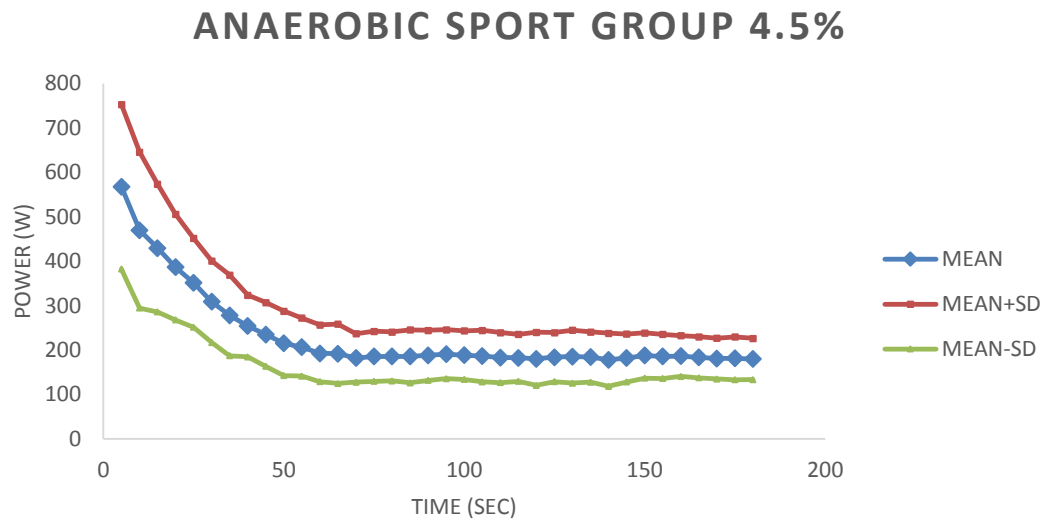


Figure 12. The mean \pm SD pattern of response for the critical power (CP) test with the resistance set at 4.5% body weight for the anaerobic sport group. Middle line indicates the mean response with \pm standard deviation above and below the mean.

ANAEROBIC SPORT GROUP 4%

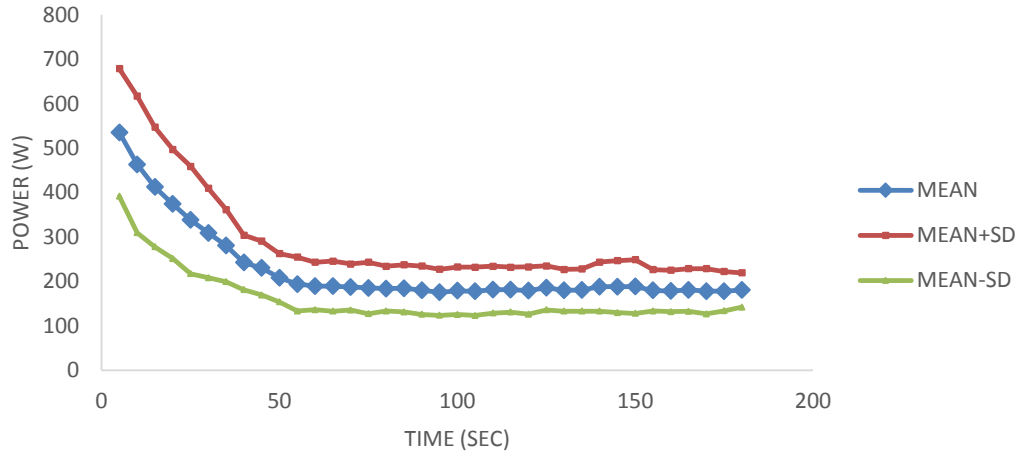


Figure 13. The mean \pm SD pattern of response for the critical power (CP) test with the resistance set at 4% body weight for the anaerobic sport group. Middle line indicates the mean response with \pm standard deviation above and below the mean.

ENDURANCE GROUP 4.5%

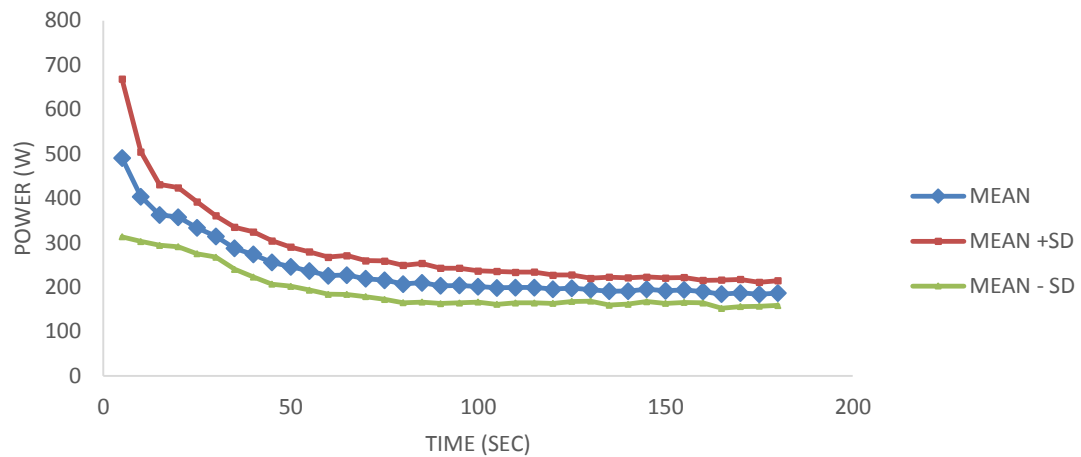


Figure 14. The mean \pm SD pattern of response for the critical power (CP) test with the resistance set at 4.5% body weight for the endurance trained group. Middle line indicates the mean response with \pm standard deviation above and below the mean.

ENDURANCE TRAINED GROUP 5%

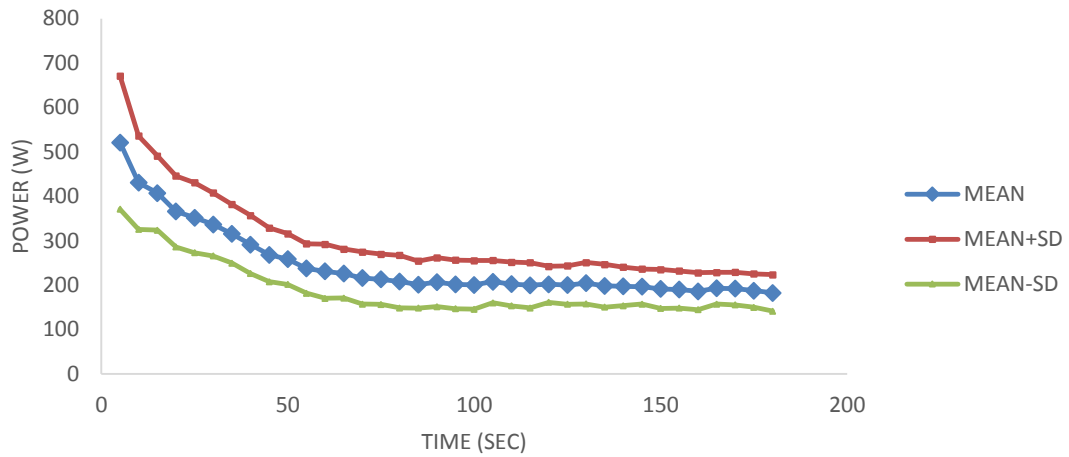


Figure 15. The mean \pm SD pattern of response for the critical power (CP) test with the resistance set at 5% body weight for the endurance trained group. Middle line indicates the mean response with \pm standard deviation above and below the mean.

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National Strength and Conditioning Association (October 2012 - Current)

- ID Number: 7247832986

Certified Personal Trainer – American Council on Exercise (March 2012 - Current)

- Certification Number: T162230

Golf Fitness Specialist – National Academy of Sports Medicine (July 2013)

- Certificate Number: 1453044

Experience

Teaching Assistant – University of Kentucky, Lexington, KY (August 2014 – Present)

Performance Coach – DiNardo Sports Performance, Lexington, KY (July 2014 – Present)

Personal Trainer & Golf Fitness Specialist – Body Structure Medical Fitness, Lexington, KY (April 2013 – July 2014)

Anatomy & Physiology Instructor – Lexington Healing Arts Academy, Lexington, KY (Summer Term 2014)

Personal Training Mentor – Lexington Healing Arts Academy, Lexington, KY (November 2013 – Present)

Group Exercise Instructor – HealthWorx Fitness & Wellness, Lexington, KY (January – March 2013)

Personal Trainer – Urban Active/LA Fitness, Lexington, KY (March 2012 - April 2013)

Varsity Women's Golf Team Member and Captain – Georgetown College, Georgetown, KY (Fall 2008 – Spring 2012)