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## Estimates of Critical Power and Anaerobic Work Capacity from a Single, All-Out Test of Less than 3-Min

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### Abstract

The purpose of this study was to determine if Critical Power (CP) and Anaerobic Work Capacity (AWC) could be estimated from a single, all-out test of less than 3-min. Twenty-eight subjects (mean  $\pm$  SD: age 23.3  $\pm$  3.3 years, body mass 71.6  $\pm$  16 kg) performed an incremental cycle ergometer test to exhaustion to determine peak oxygen consumption rate and heart rate peak. The 3-min all-out test was used to determine the criterion and six estimated values of CP and AWC. The criterion critical power (CP<sub>180</sub>) and anaerobic work capacity (AWC<sub>180</sub>) values were determined from the 3-min all-out test and were expressed as 30-s averages (155-180-s). The six estimated CP and AWC values were calculated from 30-s averages at decreasing 10-s intervals from 145 to 170-s (CP<sub>170</sub> and AWC<sub>170</sub>), 135 to 160-s (CP<sub>160</sub> and AWC<sub>160</sub>), 125 to 150-s (CP<sub>150</sub> and AWC<sub>150</sub>), 115 to 140-s (CP<sub>140</sub> and AWC<sub>140</sub>), 105 to 130-s (CP<sub>130</sub> and AWC<sub>130</sub>), and 95 to 120-s (CP<sub>120</sub> and AWC<sub>120</sub>). Mean differences, total error, constant error, standard error of the estimate, and correlations were used to compare the criterion to the estimated CP and AWC values. The results of the present study indicated that 150-s was the shortest test duration that resulted in non-significant differences between the criterion (CP<sub>180</sub> and AWC<sub>180</sub>) and estimated CP (CP<sub>150</sub>) and AWC (AWC<sub>150</sub>) values. The subsequent validation analyses showed that there were close agreements for the estimated CP<sub>150</sub> and AWC<sub>150</sub> versus the criterion (CP<sub>180</sub> and AWC<sub>180</sub>) values. Therefore, the current findings indicated that estimates of CP and AWC were not affected by shortening the test by 30-s. Reducing the length of the test to 2.5 minutes provides a less strenuous, yet valid protocol for estimating CP and AWC.

**Keywords:** Critical Power (CP); Anaerobic Work Capacity (AWC); All-out test

### Introduction

The Critical Power (CP) test provides estimates of two parameters: CP and Anaerobic Work Capacity (AWC). Theoretically, CP represents the highest sustainable power output, while AWC is a measure of the total work that can be performed utilizing only stored energy sources within the muscle including Adenosine Triphosphate (ATP), phosphocreatine, glycogen, and the oxygen bound to myoglobin [1-3]. Critical power and AWC have been used to examine the effectiveness of exercise training programs [2,4-6], predict endurance exercise performance [5,7-9], examine the mechanisms of fatigue [4,10,11], describe the effects of prior exercise on performance [12,13], assess the exercise capacity of patients with COPD (chronic obstructive pulmonary disease) [14], determine the efficacy of nutritional supplements [15-19], examine fatigue thresholds [2,3,6,9,20,21], and demarcate the heavy from severe exercise intensity domains [9,21].

The original model of Moritani et al. [2] required three or four exhaustive workouts on a cycle ergometer to estimate CP and AWC. One objective of exercise testing is to minimize the stress on the subject, while obtaining valid results [22]. Therefore, to improve its practicality, previous studies [10,21] have examined and modified the original CP test of Moritani et al. [2]. For example, Housh et al. [10] reported that instead of three or four workouts, only two exhaustive workouts were needed to accurately estimate CP and AWC. Recently, Vanhatalo et al. [21] showed that the 3-min all-out test, proposed by Burnley et al. [12], could be used to estimate CP and AWC. The protocol of Vanhatalo et al. [21], however, requires the measurement and analysis of expired gas samples during an incremental test to exhaustion on an electronically braked cycle ergometer, to determine the power output used for the 3-min all-out test [12,21]. Therefore, Bergstrom et al. [23] proposed that CP and AWC could be estimated from the 3-min all-out test and a single workout by setting the resistance according to the subject's body weight. While both of the 3-min all-out tests of Vanhatalo et al. [21] and Bergstrom et al. [23] reduced the amount of time required

to estimate CP and AWC, the demanding nature of an all-out test of 3-min duration may affect the motivation of the subjects to provide a maximal effort throughout the test and limit its application depending on the fitness level of the subjects.

Previous studies have suggested that it may be possible to estimate CP and AWC from an all-out test that is shorter than 3-min. For example, it has been suggested [24] that anaerobic work capacity reaches its maximum value within 2 min of all-out exercise. In addition, Burnley et al. [12] indicated that the power output at 2-min was not significantly different from the power output at the end of the 3-min all-out test. Thus, if the length of the test could be reduced, it would provide a less strenuous protocol to estimate CP and AWC. Therefore, the purpose of this study was to determine if accurate estimates of CP and AWC could be obtained from an all-out test of less than 3-min. Based on previous studies [12,24], we hypothesized that the all-out test could be shortened to 2-min without affecting the CP or AWC.

### Methods

#### Subjects

Twenty-eight subjects (14 male and 14 female, mean  $\pm$  SD: age

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23.3 ± 3.3 years, body mass 71.6 ± 16 kg, height 175.3 ± 10.2 cm) volunteered for this study. The subjects were moderately trained [22], and none were competitive cyclists. According to the American College of Sports Medicine [22], moderate training includes aerobic activity performed for a minimum of 30 min five times a week. Specifically, the subject's physical activities included running (n = 20), cycling (n = 14), and recreational sports (n = 6). This study was approved by the University Institutional Review Board for Human Subjects and all subjects completed a health history questionnaire and signed a written informed consent document before testing.

## Procedures

**Determination of  $\dot{V}O_2$  peak and gas exchange threshold:** Each participant performed an incremental test to exhaustion on a calibrated Lode (Corval V3, Groningen, the Netherlands) electronically-braked cycle ergometer at a pedal cadence of 70 rev·min<sup>-1</sup>. The ergometer seat height was adjusted so that the subject's legs were near full extension at the bottom of the pedal revolution. Toe clips were used to maintain pedal contact throughout the test. All participants wore a nose clip and breathed through a 2-way valve (Hans Rudolph 2700 breathing valve, Kansas City, MO, USA). Expired gas samples were collected and analyzed using a calibrated TrueMax 2400 metabolic cart (Parvo Medics, Sandy, UT, USA). The gas analyzers were calibrated with room air and gases of known concentration prior to all testing sessions. The O<sub>2</sub>, CO<sub>2</sub>, and ventilatory parameters were expressed as 30-s averages [25]. The participants were fitted with a Polar Heart Watch system to record heart rate (Polar Electro Inc., Lake Success, NY). The test began at 50 W and the power output was increased by 30 W every 2 min until voluntary exhaustion or the subject's pedal rate fell below 70 rev·min<sup>-1</sup> for more than 10 seconds, despite strong verbal encouragement. The  $\dot{V}O_2$  peak was defined as the highest  $\dot{V}O_2$  value in the last 30 s of the test that met two of the following three criteria [25]: 1) 90% of age-predicted maximum heart rate; 2) respiratory exchange ratio >1.1; and 3) a plateau of oxygen uptake (less than 150 mL·min<sup>-1</sup> in  $\dot{V}O_2$  over the last 30 s of the test).

The Gas Exchange Threshold (GET) was determined using the V-slope method described by Beaver et al. [26]. 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  $\dot{V}O_2$  relationship.

**Critical power 3-min all-out test:** Critical power was determined on the calibrated Lode electronically-braked cycle ergometer, using the procedures of Vanhatalo et al. [21]. To be consistent with the terminology of Moritani et al. [2], the term CP was used to represent the End Power (EP) and AWC was used to represent work done above end power (WEP) as described by Vanhatalo et al. [21]. Each subject completed a warm-up at 50 W for 5-min followed by 5 min of rest. The test began with unloaded cycling at 90 rev·min<sup>-1</sup> for 3 min followed by a 3 min all-out effort at the determined resistance. The participants were instructed to increase the pedaling cadence to 110 rev·min<sup>-1</sup> in the last 5 s of the unloaded phase and then maintain the cadence as high as possible throughout the 3 min test. The resistance for the test was set using the linear mode of the electronically-braked cycle ergometer (linear factor = power/cadence<sup>2</sup>). The linear factor was calculated as the power output halfway between  $\dot{V}O_2$  peak and GET (GET + 50%  $\Delta$ ) divided by a cadence of 70 rev·min<sup>-1</sup> squared [12,21]. Thus, the linear factor was equal to GET + 50%  $\Delta$  / (70 rev·min<sup>-1</sup>)<sup>2</sup>. To prevent pacing and ensure an all out effort, the participants were not made aware of the elapsed time and strong verbal encouragement was provided. The criterion measure of CP (CP<sub>180</sub>) was the average power output over

the final 30-s (155-s to 180-s) of the test and the criterion measure of AWC (AWC<sub>180</sub>) was calculated as the integral of the power versus time relationship above CP [21]. Six estimated values of CP (CP<sub>170</sub>, CP<sub>160</sub>, CP<sub>150</sub>, CP<sub>140</sub>, CP<sub>130</sub>, CP<sub>120</sub>) and AWC (AWC<sub>170</sub>, AWC<sub>160</sub>, AWC<sub>150</sub>, AWC<sub>140</sub>, AWC<sub>130</sub>, AWC<sub>120</sub>) were also calculated from 30-s averages at decreasing 10-s time intervals from 170-s to 120-s (i.e., the estimates were calculated from 30-s averages from 145 to 170-s, 135 to 160-s, 125 to 150-s, 115 to 140-s, 105 to 130-s, and 95 to 120-s).

**Statistical analyses:** Mean differences among the criterion and estimated CP and AWC values were compared with separate one-way repeated measures ANOVAs at an alpha of  $p < 0.05$ . *Post-hoc* comparisons were performed using paired *t*-tests at a Bonferroni corrected alpha of  $p < 0.0071$  (0.05/7) (Table 1). Separate zero-order correlation matrices were used to determine the relationships among the criterion and estimated CP and AWC values (Tables 2 and 3). Further validation analyses were based on the evaluation of the criterion versus estimated CP and AWC via calculations of the total error (TE =  $\sqrt{\sum [criterion - estimated]^2 / n}$ ), constant error (CE = criterion - estimated), standard error of the estimate (SEE (Standard Error of the Estimate) =  $SD \sqrt{1 - r^2}$ ), correlations between CE and criterion values, and the similarity between the standard deviations of the criterion and estimated values (Table 4). In addition, the data have been presented using the method of Bland and Altman [27]. The analyses were conducted using Statistical Package for the Social Sciences software (v.19.0. SPSS Inc., Chicago, Illinois, USA).

The following criteria were used in the present study to evaluate the results of the validation analyses: (a) the mean values for the criterion CP and AWC should not be significantly different from the estimated values; (b) there should be close similarity between the TE and SEE; (c) there should be no significant correlation between the CE and the criterion measures; (d) there should be a high correlation between the criterion and estimated values; (e) there should be close agreement between the standard deviation values of the criterion and estimated values.

## Results

The mean (± SD)  $\dot{V}O_2$  peak for the subjects in this study was 42.2 ± 7.1 mL·kg<sup>-1</sup>·min<sup>-1</sup> and the maximal power output for the incremental test to exhaustion was 231 ± 51 W. In addition, the GET (27.7 ± 5.2 mL·kg<sup>-1</sup>·min<sup>-1</sup>) occurred at 66% of  $\dot{V}O_2$  peak and 60% of maximal power output (139 ± 37 W).

A one-way repeated measures ANOVA indicated that there were no significant differences among CP<sub>180</sub> (187 ± 47 W), CP<sub>170</sub> (189 ± 49 W), CP<sub>160</sub> (191 ± 50 W), CP<sub>150</sub> (192 ± 51 W), and CP<sub>140</sub> (193 ± 51 W) (Table 1). In addition, no significant differences were found among AWC<sub>180</sub> (10.2 ± 3.4 kJ), AWC<sub>170</sub> (9.9 ± 3.5 kJ), AWC<sub>160</sub> (9.7 ± 3.4 kJ), and AWC<sub>150</sub> (9.5 ± 3.3 kJ) (Table 1). Thus, 150-s was the shortest test duration that resulted in non-significant differences between both the criterion (CP<sub>180</sub> and AWC<sub>180</sub>) and estimated CP (CP<sub>150</sub>) and AWC (AWC<sub>150</sub>) values (Figure 1). Therefore, the subsequent validation analyses were performed between the estimated CP<sub>150</sub> and AWC<sub>150</sub> values versus the criterion values (CP<sub>180</sub> and AWC<sub>180</sub>) (Table 4). The SEE and TE values for CP were 9 W and 10 W, respectively. The SEE and TE values for AWC were 1.2 kJ and 1.4 kJ, respectively. The TE represented 5.5% and 13.7% of the mean values for the CP<sub>180</sub> and AWC<sub>180</sub> values, respectively. In addition, there were non-significant ( $p > 0.05$ ) correlations for the CE versus CP<sub>180</sub> ( $r = -0.24$ ) and the CE versus AWC<sub>180</sub> ( $r = 0.27$ ) (Figures 2 and 3). The CP<sub>180</sub> was highly

Time (s)	180	170	160	150	140	130	120
CP (W)	187 ± 47	189 ± 49	191 ± 50	192 ± 51	193 ± 51	196 ± 52 <sup>†</sup>	199 ± 54 <sup>†</sup>
AWC (kJ)	10.2 ± 3.4	9.9 ± 3.5	9.7 ± 3.4	9.5 ± 3.3	9.3 ± 3.1 <sup>†</sup>	9.0 ± 3.0 <sup>†</sup>	8.8 ± 3.1 <sup>†</sup>

significantly different from CP<sub>180</sub> at a Bonferroni corrected alpha of  $p < 0.0071$  (0.05/7)  
<sup>†</sup>significantly different from AWC<sub>180</sub> at a Bonferroni corrected alpha of  $p < 0.0071$  (0.05/7)

**Table 1:** Mean (± SD) values for six estimated (170-s, 160-s, 150-s, 140-s, 130-s, and 120-s) and criterion (180-s) measures of Critical Power (CP) and Anaerobic Work Capacity (AWC).

	CP <sub>180</sub>	CP <sub>170</sub>	CP <sub>160</sub>	CP <sub>150</sub>	CP <sub>140</sub>	CP <sub>130</sub>	CP <sub>120</sub>
CP <sub>180</sub>	1.00						
CP <sub>170</sub>	1.00	1.00					
CP <sub>160</sub>	0.99	1.00	1.00				
CP <sub>150</sub>	0.98	0.99	1.00	1.00			
CP <sub>140</sub>	0.98	0.98	0.99	1.00	1.00		
CP <sub>130</sub>	0.97	0.97	0.98	0.98	1.00	1.00	
CP <sub>120</sub>	0.96	0.96	0.97	0.97	0.99	1.00	1.00

**Table 2:** Correlation matrix for Critical Power (CP) among the estimated (CP<sub>170</sub>, CP<sub>160</sub>, CP<sub>150</sub>, CP<sub>140</sub>, CP<sub>130</sub>, CP<sub>120</sub>) and criterion (CP<sub>180</sub>) values.

	AWC <sub>180</sub>	AWC <sub>170</sub>	AWC <sub>160</sub>	AWC <sub>150</sub>	AWC <sub>140</sub>	AWC <sub>130</sub>	AWC <sub>120</sub>
AWC <sub>180</sub>	1.00						
AWC <sub>170</sub>	0.98	1.00					
AWC <sub>160</sub>	0.96	0.99	1.00				
AWC <sub>150</sub>	0.93	0.97	0.99	1.00			
AWC <sub>140</sub>	0.91	0.93	0.97	0.98	1.00		
AWC <sub>130</sub>	0.88	0.89	0.93	0.94	0.98	1.00	
AWC <sub>120</sub>	0.79	0.81	0.84	0.86	0.92	0.96	1.00

**Table 3:** Correlation matrix for Anaerobic Work Capacity (AWC) among the estimated (AWC<sub>170</sub>, AWC<sub>160</sub>, AWC<sub>150</sub>, AWC<sub>140</sub>, AWC<sub>130</sub>, and AWC<sub>120</sub>) and criterion (AWC<sub>180</sub>) values.

	Constant Error (CE)	Stadard Error of the Estimate (SEE)	Total Error (TE)
CP <sub>150</sub> vs. CP <sub>180</sub>	-5 W	9 W	10 W
AWC <sub>150</sub> vs. AWC <sub>180</sub>	0.7 kJ	1.2 kJ	1.4 kJ

**Table 4:** Validation analyses (n = 28) for the estimated critical power (CP<sub>150</sub>) and anaerobic work capacity (AWC<sub>150</sub>) values versus the criterion CP<sub>180</sub> and AWC<sub>180</sub>.

correlated with the estimated CP<sub>150</sub> ( $r = 0.98$ ) (Table 2). There was also a high correlation ( $r = 0.93$ ) between AWC<sub>180</sub> and the estimated AWC<sub>150</sub> (Table 3). Furthermore, the standard deviations for the CP<sub>180</sub> (47 W) and AWC<sub>180</sub> (3.4 kJ) values were similar to those of the estimated CP<sub>150</sub> (51 W) and AWC<sub>150</sub> (3.3 kJ) values.

## Discussion

The results of the present study, as well as those of previous studies [12,24], suggested that it is possible to estimate CP and AWC from a single, all-out workout of less than 3 minutes duration. For example, Burnley et al. [12] indicated that there was no significant change in power output over the last minute of the 3-min test (120 to 180-s) and suggested that it may be possible to estimate CP from a shorter test. During the 3-min all-out test, Burnley et al. [12] found that the power output at 120-s was only 5 W (2%) greater than the power output at 180-s. Furthermore, when 30-s averages were considered, Burnley et al. [12] reported that average power outputs after 135-s were not significantly different from the final power output. In addition, Medbø et al. [24] found that the treadmill analog of AWC for cycle ergometry called the Anaerobic Running Capacity (ARC), was equal to the maximal accumulated oxygen deficit (oxygen deficit = the difference between oxygen demand and oxygen uptake) during exhaustive running for 2-min at supramaximal intensities. Thus, Medbø et al. [24] suggested that anaerobic stores were exhausted and, therefore, ARC would not change significantly after 2-min of an all-out test. The current findings indicated that there were no significant differences

between the estimated CP<sub>150</sub> and AWC<sub>150</sub> and the criterion CP<sub>180</sub> and AWC<sub>180</sub> values, respectively. These non-significant differences were evaluated as 30-s averages beginning at 2-min and, thus, supported the findings of Burnley et al. [12] and Medbø et al. [24]. Therefore, the results of the present study indicated that the 3-min all-out test could be shortened to 2.5-min without affecting the estimated values for CP and AWC. Reducing the length of the test by 30-s, results in a less strenuous protocol to estimate CP and AWC.

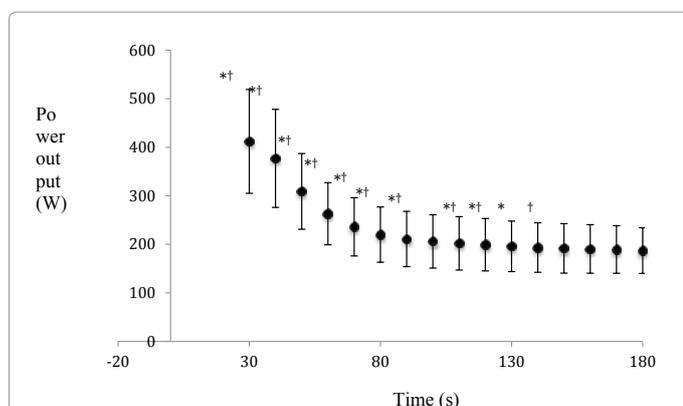
The results of the validation analyses in the present study provided additional support for shortening the all-out test from 3 to 2.5-min. For example, the power output at CP<sub>150</sub> was only 2.7% (CE = -5 W) greater than the power output at CP<sub>180</sub> and the AWC<sub>150</sub> value was 6.9% (CE = 0.7 kJ) lower than the AWC<sub>180</sub> value. In addition, there were high correlations between CP<sub>150</sub> and CP<sub>180</sub> ( $r = 0.98$ ), as well as AWC<sub>150</sub> and AWC<sub>180</sub> ( $r = 0.93$ ). Furthermore, the SD values for CP<sub>150</sub> and AWC<sub>150</sub> (51W and 3.3 kJ, respectively) were 4 W greater and 0.1 kJ less than the SD values for CP<sub>180</sub> and AWC<sub>180</sub> (47 W and 3.4 kJ, respectively). Thus, these findings indicated that there were close agreements between the estimated and criterion CP and AWC values.

The SEE for CP<sub>150</sub> and AWC<sub>150</sub> were 4.8% and 11.8% of the mean CP<sub>180</sub> and AWC<sub>180</sub>, respectively. The TE for CP<sub>150</sub> and AWC<sub>150</sub> were 5.5% and 13.7% of the mean CP<sub>180</sub> and AWC<sub>180</sub>, respectively. The differences between the estimated and criterion SEE and TE values were 1 W and 0.2 kJ for CP and AWC, respectively. In the present study, the close similarity between the SEE and TE was due, primarily, to the small CE values.

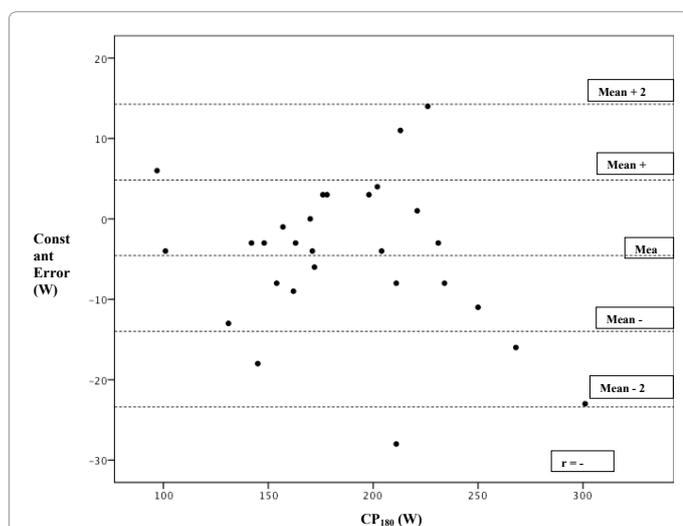
Bland and Altman plots [27] were used to describe the distributions of the CE versus criterion ( $CP_{180}$  and  $AWC_{180}$ ) values (Figures 2 and 3). Figures 2 and 3 indicated that the CE values remained stable across the criterion measures. Furthermore, the correlation coefficients ( $r$ ) for the CE values versus  $CP_{180}$  and  $AWC_{180}$  were not significantly different from zero at  $r = -0.24$  and  $r = 0.27$ , respectively. Thus, the current findings indicated that the magnitude of the CE values were not affected by the subject's levels of CP or AWC.

## Conclusions

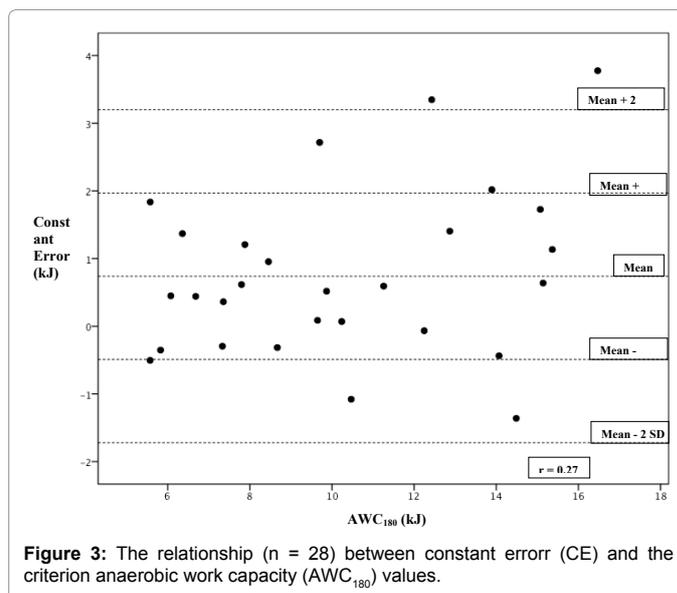
The 3-min all-out test has been proposed as a less time consuming alternative to the original multiple exhaustive workout model of Moritani et al. [2] for estimating CP and AWC. The demanding nature of this test, however, limits its practicality. Thus, we examined the accuracy of CP and AWC estimates from shorter test durations. The results of the present study showed that there were no significant mean differences and close agreements between  $CP_{150}$  and  $CP_{180}$ , as well as



**Figure 1:** Mean ( $\pm$  SD) 30-s averaged power outputs for all subjects ( $n = 28$ ) during the 3-min all-out critical power (CP) test. The error bars indicate standard deviations. The asterisks indicate a significant difference in CP estimates from the criterion ( $CP_{180}$ ) and the crosses ( $\dagger$ ) indicate a significant difference in anaerobic work capacity (AWC) estimates from the criterion ( $AWC_{180}$ ). The results indicated that 150-s was the shortest test duration that resulted in non-significant differences between the criterion ( $CP_{180}$  and  $AWC_{180}$ ) and estimated CP ( $CP_{150}$ ) and AWC ( $AWC_{150}$ ) values.



**Figure 2:** The relationship ( $n = 28$ ) between constant error (CE) and the criterion critical power ( $CP_{180}$ ) values.



**Figure 3:** The relationship ( $n = 28$ ) between constant error (CE) and the criterion anaerobic work capacity ( $AWC_{180}$ ) values.

between  $AWC_{150}$  and  $AWC_{180}$ . Therefore, the current findings indicated that estimates of CP and AWC were not affected by shortening the test by 30-s. Reducing the length of the test provides a less strenuous, yet valid protocol for estimating CP and AWC. Future studies should examine the metabolic responses and times to exhaustion at CP determined from the 2.5-min all-out test and validate the 2.5-min protocol against other fatigue thresholds.

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