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Characterization and Reliability of the Work-Time Relationship During Arm-Cranking

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CHARACTERIZATION AND RELIABILITY OF THE WORK-TIME RELATIONSHIP DURING ARM-CRANKING

by

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ABSTRACT

INTRODUCTION: The critical power (CP) exercise test provides 2 measures, CP and anaerobic working capacity (AWC). CP represents a fatigue threshold that separates the heavy and severe exercise domains, while AWC represents the finite amount of work that can be done above CP. A relatively new protocol for estimating CP has emerged and is described as the 3-minute all-out test (3MT). While this lower body 3MT test has been examined for validity and reliability, very little has been done for the upper body. **PURPOSE:** Examine the reliability of EP and WEP from the 3MT during upper-body ergometry. This study also compares the traditional CP test vs. 3MT methods for estimating CP and AWC. **METHODS:** 15 recreationally active men (age: 23 ± 2.6 y; height: 175 ± 4.5 cm; weight: 86.8 ± 14.4 kg; body fat: 20.7 ± 7.8% body fat) completed a graded exercise test to exhaustion on an arm ergometer to determine peak power output (PPO). Participants completed two 3-minute all-out tests (3MT) on different days. Finally, each participant completed three constant work-rate arm-cranking tests at 90, 100, and 110% PPO. Linear regression was used to estimate CP and AWC via the work-time relationship during the constant work-rate tests. EP and WEP were determined using the work-time integral during the 3MT. **RESULTS:** ICC values for EP (.90) and TW (.956) revealed excellent reliability, while AWC (.783) had good reliability. CP estimated from the traditional method was significantly different from EP estimated from 3MT (t[14] = -3.631; p = 0.003). W' estimated from the traditional method was not significantly different from WEP estimated from 3MT (t[14] = .185; p = .856). **CONCLUSIONS:** The 3-minute all-out test (3MT) is a reliable method for estimating EP during upper-body ergometry.

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CHAPTER ONE: INTRODUCTION

The critical power (CP) concept represents the work-time relationship observed during many exercise modalities (Jones et al., 2010). CP, the primary measure of the work-time relationship, describes the workload a muscle group can maintain without reaching exhaustion (Monod and Scherrer, 1965). Another way to describe CP is as a fatigue threshold that separates the heavy and severe exercise domains (Jones et al., 2010, Poole et al., 2016). Exercise taking place above CP will eventually lead to exhaustion, as well as increased intramuscular acidity and blood lactate concentrations (Poole et al., 2016, Jones et al., 2010, Taylor and Batterham, 2002). The second parameter in the work-time relationship is W' (or anaerobic working capacity AWC) which is characterized as a finite amount of work that can be done above CP (Jones et al., 2010, Townsend et al., 2017). Theoretically, upon depletion of W' at work rates above CP, exhaustion will occur, and the activity must end.

The CP concept was originally applied to lower-body resistance training (Monod and Scherrer 1965) before expanding to lower-body aerobic activities such as treadmill running and cycle ergometry (Moritani et al., 1981, Hughson et al., 1984). More recently, the CP concept has been applied during upper-body modalities (Taylor and Batterham 2002). The upper body has a larger proportion of type II muscle fibers than the lower body with a lower overall muscle mass, causing an early reliance on anaerobic metabolism (Calbet et al., 2003; Sanchis- Moysi et al., 2010; Martin et al., 1991). This early reliance on anaerobic metabolism, combined with other morphological factors (Martin, Zeballos, & Weisman, 1991), such as larger diffusion distances due to fewer capillaries per muscle fiber (Calbet et al., 2005), limits the aerobic capacity of the upper-body which consistently produces maximal VO2 values around 70% of what is observed in the lower-body (Martin et al., 1991). Earlier reliance on anaerobic metabolism suggests fatigue thresholds such as ventilatory threshold (VT) and respiratory compensation point (RCP) may occur earlier as well during incremental exercise. RCP and CP are often identified as occurring at the same power outputs (Bergstrom et al., 2013); therefore, we can theorize that CP will occur earlier as well.

CP is a valuable performance measure to many athletic populations but is rarely assessed due to the time commitment required to estimate it (Jones et al., 2010). Traditionally, to estimate CP, three to five separate exercise tests are necessary to model the work-time relationship accurately. First, a test to measure peak power is needed; graded exercise tests (GXT) are most commonly used. Once peak power is measured, three to five constant-work-rate (CWR) trials are performed at intensities surrounding peak power (e.g., 80%, 90%, 100%, 110%, 120%) (Galbraith et al., 2014). Total work is plotted against time for each CWR trial, and linear regression is applied, creating the two-parameter critical power model (Jones and Vanhatalo 2017). In this linear model, the slope of the regression is CP, and the y-intercept is W'. This method provides a reliable way to estimate CP during lower body exercise (Smith and Hill 1993; Gaesser and Wilson 1988).

Recently, a more time-efficient method for estimating CP has emerged. This new method, called the 3-minute all-out test (3MT), aims to estimate CP and W' that is less cumbersome (Burnley et al., 2006). During the 3MT, a resistance based upon the participant's body mass is applied to the ergometer (Bergstrom et al., 2012). The participant is instructed to accelerate to their maximum and maintain that effort for the duration of the test. CP is determined by averaging the power output in the last 30 seconds of the test and is called end test power (EP). W' called work above end power (WEP) in the 3MT is the power-time integral above end power (Vanhatalo et al., 2008). This 3MT has been effectively applied to the lower body via cycle ergometry (Burnley et al., 2006) and is found to be a valid and reliable means for estimating CP during lower body exercise (Vanhatalo et al., 2007; Vanhatalo et al., 2008).

The CP concept has also been applied during exercise modalities that utilize the upper-body musculature, where a linear work-time relationship is observed (Capodaglio and Bazzini 1996). Initially, the traditional CP method was employed during upper-body cycling, where five sets of constant power tests were performed twice (Taylor and Batterham 2002). High variation in parameter estimates has been observed for both CP and W' when utilizing the traditional method of CP estimation during upper-body ergometry (Taylor and Batterham 2002). Recently, the 3MT has been applied to upper-body ergometry where excellent reliability parameters (ICC's > .922) were noted for all power measurements automatically measured on the ergometer except time to peak power (Flueck 2017). With almost all power parameters showing excellent reliability during a 3MT, the opportunity to examine estimates of CP and W' presents itself.

The purpose of this investigation is to examine the reliability of CP and W' estimated from a 3MT during upper-body ergometry. A secondary goal of this study is to compare EP and WEP from the 3MT to CP and W' derived from the traditional method. Considering the data seen in the lower body, our hypothesis is that CP and W' estimated from the 3MT will be reliable and provide similar values to the traditional method.

CHAPTER TWO: METHODOLOGY

Participants

Recreationally trained males between the ages of 18 and 35 were screened for eligibility using a Physical Activity Readiness Questionnaire (PAR-Q+) and confidential Medical History and Activity Questionnaire (MHAQ). Informed consent was reviewed privately with each participant prior to enrolling in this investigation. Participants were instructed to maintain daily physical activity and their normal diet throughout the study. Before maximal testing, participants were asked to avoid any strenuous physical activity the day before the test. Individuals were excluded if they had recent musculoskeletal injuries or surgeries, any chronic illness that required continuous medical care, current incarceration, cognitive impairment, or inability to provide consent, or present or past use of performance-enhancing drugs. This protocol was reviewed and approved by the University of Central Florida's institutional review board.

Research Design

To test the hypotheses, this investigation follows a within-subject repeated measures design. After the informed consent (T1), each participant was assessed for their anthropometric measures and body composition and completed an incremental exercise test to volitional exhaustion on an upper-body ergometer. On the second visit (T2), participants completed the first of two 3-minute all-out tests (3MT). On the third visit (T3), participants completed the second 3-minute test (3MT). Finally, on the fourth visit (T4), participants completed three randomized time trials at (90%, 100%, and 110%) of peak power output.

Anthropometry and Body Composition

Anthropometrics were obtained by a stadiometer for body height and scale for body mass (500KL Health O Meter, Alsip, IL, USA) on the first visit following informed consent. Body fat percent was obtained from a multifrequency bioelectrical impedance analysis device (Inbody 770, USA). For body composition analysis, participants were instructed to wear minimal clothing. In addition, they were required to remove all jewelry, shoes, and socks. Each subject was asked to stand on a scale with two handles for one minute to obtain measurements for body composition.

Incremental Testing Protocol

During T1, an incremental test to volitional exhaustion was performed on an upper-body ergometer (891E, Monark Upper Body Ergometer, Vansbro, Sweden). During this test, participants' heart rates were recorded. Chest strap heart rate monitors were used (Polar H10), and the participants secured the monitor themselves. The participants performed a three-minute warm-up at 50 W; they were required to maintain a cranking cadence of 50 revolutions per minute (RPM) at an initial 50 W workload. The workload then increased 20 W every two minutes until the participant could not maintain a cadence above 50 RPM for 5 seconds despite verbal encouragement or volitional fatigue (La Monica et al., 2018). Peak power will be determined as the highest power output completed during a two-minute stage.

3-Minute Test (3MT)

During T2 and T3, participants returned to the POWER laboratory. A 3-minute all-out test was performed on an upper-body ergometer (891E, Monark Upper Body Ergometer, Vansbro, Sweden) to measure end power (EP) and work above end power (WEP). First, participants performed a three-minute warm-up at 50 W, followed by 1 minute of rest. After the 1-minute rest period, participants were instructed to start cranking as fast as possible, and 3-7 seconds after that, a resistance of two percent of their body mass was applied to the ergometer. Participants were asked to keep cranking as fast as possible for 3 minutes with strong verbal encouragement throughout. This test ended after 3 minutes or whenever the participant could not keep cranking the handles. CP is estimated from the average power of the last 30 seconds of the test, and AWC was measured from work completed above CP. Peak power is defined as the highest power output achieved during the test, and time to that peak power was also recorded.

Multi-Trial Critical Power Test

During T4, the participants completed a multi-trial critical power test on an upper-body ergometer (891E, Monark Upper Body Ergometer, Vansbro, Sweden) to measure CP and AWC. Following a 3-minute warm-up at 50 W, the participants performed three randomized time trials at (90%, 100%, and 110%) of PPO achieved during the graded exercise and maintained 50 rpm throughout the test which were separated by a minimum of 15 minutes of rest. Linear regression was used to determine the slope of the line from the relationship between TTE and TW for each set of trials. According to the work-time model (Smith, Stephens, Hall, Jackson, & Earnest, 1998), the slope of the regression line was considered CP while the y-intercept was deemed AWC.

Statistical Analysis

All statistical analyses were conducted via the Statistical Package for Social Science (SPSS) software for Windows version 25 (SPSS Inc., Chicago, IL). Dependent variables (EP, WEP, CP, AWC, TW) were analyzed using a dependent T-Test to determine where significant differences exist. Relevant correlation analyses were conducted for comparisons of CP and EP as well as AWC and WEP. Intraclass correlation coefficients (ICC; model 2,1) (Weir 2005), standard error of measurement (SEM), the minimal difference (MD), and 95% confidence intervals for mean differences were used to compare the reliability of EP, WEP, and TW during the 3 min all-out tests. EP was evaluated against the traditional multi-trial estimate of CP by calculating the constant error (CE = multi-trial CP – 3MT EP Watts), Pearson product-moment correlation coefficient (r), standard error of estimate (SEE), and total error (TE). Additionally, the method of Bland and Altman (1983) was used to identify the 95% limits of agreement between the traditional method and 3MT variables.

CHAPTER THREE: RESULTS

The estimates for the variables from 3MT1, 3MT2, and the multi-trial CP test are listed in table 1. CP estimated from the traditional method was significantly different from EP estimated from 3MT2 ($t[14] = -3.631$; $p = 0.003$) with a CE of -23W, SEE of +17W, TE of +33W, and was not significantly correlated ($r = 0.27$, $p = 0.337$). EP estimated from 3MT1 was not significantly different from 3MT2 ($p = 0.992$). W' estimated from the traditional method was not significantly different from WEP estimated from 3MT ($t[14] = 0.185$; $p = 0.856$) with a CE of +205J, SEE of +2644J, TE of 4152J, and was not significantly correlated ($r = -0.39$; $p = 0.075$). Figures 1 and 2 present the 95% limits of agreement via Bland-Altman plots for CP (77.3W ± 17.8W) and EP (100.3W ± 21.1W) with LOA values ranging from -70W to +24W as well as W' (6333J ± 3016J) and WEP (6128J ± 1901J) with LOA values ranging from -7923J to +8333J. In addition, the regression lines in Figures 1 and 2 are not significant ($p = 0.337$) and ($p = 0.15$), respectively, suggesting there is not a bias in mean values. All but one participant fell within 1.96 standard deviations of the mean difference for CP and W'.

The ICC, SEM, MD, and 95% CI values for EP, WEP, and TW are displayed in table 2. No significant differences were observed between any 3MT variables.

CHAPTER FOUR: DISCUSSION

This investigation is the first to examine the work-time relationship's estimations of CP and W' during a 3MT on a mechanically braked upper-body ergometer. The test-retest reliability for EP ($ICC_{2,1}$ = 0.90) and WEP ($ICC_{2,1}$ = 0.783) observed in the current investigation is in agreement with repeatability parameters observed using the traditional estimation of CP and AWC (Gaesser and Wilson 1988). Mean EP values during 3MT1 (100 ± 18W) and 3MT2 (100 ± 21W) were similar to traditional CP (96 ± 16W) (95 ±17W) values observed previously (Taylor and Batterham 2002) and (90.22 ± 12.88) (La Monica et al., 2018). The excellent ($ICC_{2,1}$ = 0.956) reliability observed for TW is in agreement with previous literature ($ICC_{2,1}$ = 0.984) (Flueck 2017). The high-reliability values observed in the current investigation can provide investigators with confidence that the 3MT remains reliable across a variety of exercise modalities.

In the current study, CP estimated from the traditional method was statistically different from EP estimates. This is similar to findings observed in the lower body where EP and CP were also statistically different (275.1±41.2 W vs. 244.9±26.2 W, P=0.004) (Wright et al., 2017) when cycling against a fixed resistance. EP has also been identified to overestimate CP by as much as 37W during lower-body cycling (Karsten et al., 2016); the mean difference noted in the current investigation is 23W. The high standard error (17W) reported between CP and EP in the current investigation conflicts with what has been observed during lower body cycling, where a smaller standard error was reported (6W) (Jones and Vanhatalo 2017) for the same relationship. During both rowing (Cheng et al., 2012) and ski ergometry (Fukuda et al., 2014), EP estimated from a 3MT was similar to CP observed during the traditional method. High TE between CP and EP (33W) suggests that the 3MT does not provide a valid estimate of CP even though the Bland-

Altman plot revealed no systematic biases between the traditional method and 3MT ($r = 0.27$, $p = 0.337$). These findings raise questions regarding the validity of the 3MT when cycling against fixed resistances during both upper and lower-body modalities.

WEP estimated in the current investigation had good reliability (ICC = .783) between 3MT1 and 3MT2. Past investigations into the reliability and validity of WEP are inconclusive, with excellent reliability (ICC = .94) reported during lower-body ergometry (Wright et al., 2017) and fair reliability (ICC = .611) reported during ski ergometry (Fukuda et al., 2014) and rowing (ICC = .628) (Cheng et al., 2012). WEP and W' were not statistically different ($p = 0.856$) in the current study but had a large total error of 4152J (~65% of the $\bar{x}$) and were not significantly correlated ($p = 0.075$). WEP was not significantly different from W' during lower-body cycling (Vanhatalo et al., 2007) or ski ergometry (Fukuda et al., 2014) but was significantly different during rowing (Cheng et al., 2012). With large total error and a wide range of reliability across modalities, it is difficult to determine if WEP estimates the same parameter as W'. Anaerobic capacity is still a theoretical construct (Green and Dawson 1993), and with large measurement errors, it is still not understood if W' and WEP represent the same quantity (Burnley 2009; Dekerle et al., 2008). Further research is needed to determine if W' and WEP are synonymous and remain similar across all exercise modalities.

The most important limitation in this investigation is that all three times to exhaustion trials were completed in one day, possibly influencing the work-time relationship used to estimate CP and W' in the traditional method. It is possible that randomizing the constant work-rate trials used to estimate CP may impact overall CP values performed on the same day. In the current study, randomly assigned individuals to the 110% trial first ended up with more shallow slopes for the work-time relationship. Similar findings are noted during a lower-body investigation into the reliability and validity of the 3MT, where randomization may have affected CP values (Wright et al., 2017). Another possible limitation is that none of these participants had specifically trained on an upper-body ergometer previously; this possibly influenced their efficiency during the movement. However, the excellent reliability observed for EP during the 3MT suggests that familiarization with the upper-body ergometer was not a factor.

In conclusion, our findings suggest that the 3MT provides reliable estimates of EP, WEP, and TW during upper-body ergometry. However, these data also suggest that the EP estimated from the 3MT is different from CP estimated from the traditional method. Therefore, further studies into the validity of EP and WEP estimates from the 3MT are needed to elucidate if the 3MT can be used in place of the traditional CP method during upper-body ergometry. To test if EP represents a true threshold, EP estimated from a 3MT could be used to compare actual time to exhaustion and predicted time to exhaustion at multiple workloads (e.g. EP-20%, EP+20%, EP+40%, EP+60%) (Housh et al., 1989), WEP could be examined in the same way.

APPENDIX A: FIGURES

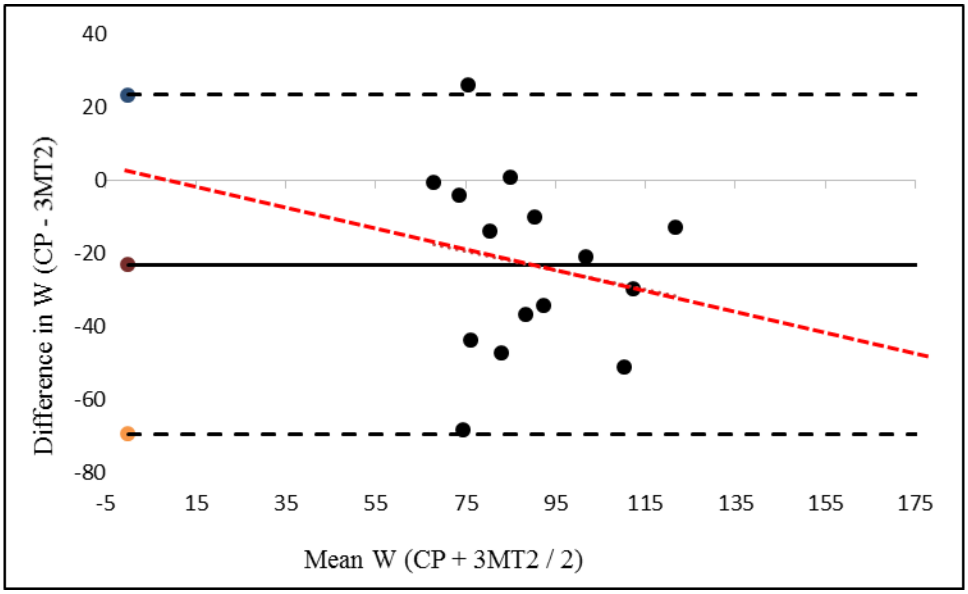

Figure 1 Bland–Altman plots for estimated values from the traditional multi-trial CP test and the second 3MT trial CP and EP. The solid line represents the bias/constant error, and the dashed line represents the 95% limits of agreement.

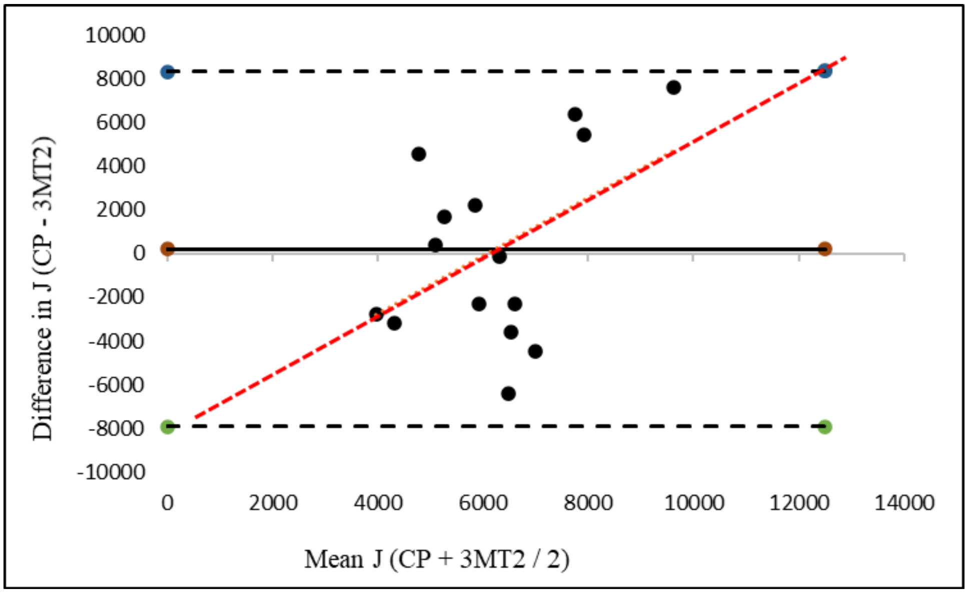

Figure 2. Bland–Altman plots for estimated values from the traditional multi-trial CP test and the second 3MT trial W' and work above EP. The solid line represents the bias/constant error, and the dashed line represents the 95% limits of agreement.

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APPENDIX B: TABLES

Table 1 Comparison of estimated values from 3 min test (3MT) trials and the multi-trial critical power test.

	Critical power estimates (W)	**W' estimates (J)**
	Mean SD	Mean SD
EP1	100.34 ± 18.25	6124.53 ± 2095.54
EP2	100.32 ± 21.06	6127.74 ± 1900.99
CP	77.3 ± 17.86	6332.65 ± 3015.85

Table 2 Test-retest reliability data for 3 min (3MT) trials.

	ICC 2.1	**SEM**	**MD**	**95 % CI 3MT1-3MT2**
EP (W)	0.900	6.68	18.53	-5 to 5
WEP (J)	0.783	965	2674	-759 to 752
TW (J)	0.956	793	2199	-807 to 435

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