

## **The reliability and validity of the 3-minute all-out cycling critical power test**

## **Abstract**

Research suggests that critical power (CP) can be estimated from a single 3-minute bout of all-out cycling. The purpose of this study was to investigate the reliability and validity of the 3-minute all-out cycling test when carried out at a constant cadence (isokinetic) and against a fixed resistance (linear). Twelve participants completed 8 tests: 1) a ramp test, 2–4) three fixed power tests to calculate CP and  $W'$  using the 1/time mathematical model, 5–8) four 3-minute all-out tests to calculate EP and WEP; two isokinetic and two linear. There was no significant difference between EP-isokinetic and CP ( $P=0.377$ ). There were significant differences between EP-linear and CP ( $P=0.004$ ), WEP-isokinetic and  $W'$  ( $P<0.001$ ) and WEP-linear and  $W'$  ( $P<0.001$ ). Coefficient of variation in EP-isokinetic, EP-linear, WEP-isokinetic and WEP-linear was 1.93%, 1.17%, 8.44% and 5.39%, respectively. The 3-minute all-out isokinetic test provides a reliable estimate of EP and a valid estimate of CP. The 3-minute all-out linear test provides a reliable estimate of EP, but not a valid estimate of CP. Furthermore, these results suggest that the 3-minute all-out test should not be used to estimate  $W'$ .

## Introduction

Athletes frequently utilise laboratory exercise testing to assist with training design and race strategy [12,24]. There are numerous testing protocols available when monitoring the physiological condition of an athlete, including lactate threshold (LT), maximal lactate steady state (MLSS) and maximal oxygen uptake ( $\dot{V}O_{2max}$ ) protocols. In comparison to LT, MLSS and  $\dot{V}O_{2max}$ , Critical Power (CP) testing can provide athletes with information about both the anaerobic and aerobic energy systems. [16]. CP has been defined as the highest sustainable rate of aerobic metabolism [15], providing an estimate of the heavy-severe exercise domain boundary [28]. Jones et al [22] stated that CP is rate- but not capacity-limited. They also suggested that there is an anaerobic component (finite work capacity), which is capacity- but not rate-limited and it is defined as the amount of work that can be completed above CP ( $W'$ ). Johnson et al. [21] recommends the use of CP testing when monitoring power adaptations to training but, although the benefits of CP testing are known, the original testing protocol is time consuming. Traditionally, the protocol involves completion of 3–8 time-to-exhaustion tests, each performed on separate days [7,13,17,18,20,25].

Due to the time-consuming nature of multi-day testing protocols, researchers have recently focused on single-day testing protocols [26]. In 2006, Brickley et al. [5] investigated the possibility of estimating  $\dot{V}O_{2max}$  and critical power from a 90-s all-out test. This was based on the assumption that  $W'$  is finite and, if fully depleted, would result in a power output being maintained from only aerobic metabolism and therefore equal to CP. The results of this study suggested that a longer test was required to elicit a power output that corresponds to CP leading to the development of the 3-minute all-out cycling test [6]. Burnley et al. [6] concluded that the 3-minute test could be used to establish  $\dot{V}O_{2peak}$  and MLSS, which may prove to be beneficial over traditional multi-day testing protocols. Further studies have suggested that CP and  $W'$  can be estimated from the 3-minute all-out cycling test [29] and that this test provides a reliable estimate of CP. The estimates of CP and  $W'$  were consequently termed end power (EP) and work above end power (WEP), respectively [28].

The 3-minute all-out test was originally carried out using the Lode Excalibur Sport cycle ergometer, utilising a fixed resistance (linear mode). This fixed resistance was set using the following equation: linear factor (resistance) = power output/preferred cadence<sup>2</sup>, where power output is determined as the midway point between gas exchange threshold (GET) and  $\dot{V}O_{2peak}$  [28]. With the linear mode being unique to the Lode Excalibur Sport, this provides a potential limitation of the original testing protocol unless it can be established that the 3-minute all-out test can also be carried out on other cycle ergometers. Several studies have investigated the reliability and validity of the 3-minute all-out test using alternative cycle ergometers and testing modes, for example the Monark ergometer, CompuTrainer and SRM ergometer in isokinetic mode [3,18,23]. Due to the physiological basis of the original test, Karsten et al. [18] argued that an agreement between the EP observed during the 3-minute all-out test and CP from original methods, along with  $W'$  and the estimate WEP, should be seen irrespective of the mode of measurement. However, Karsten et al. [18] found that, whilst providing a reliable estimate of EP, the SRM ergometer set in isokinetic mode overestimated CP by approximately 35 W. The results of this study also suggested that the isokinetic mode does not provide a reliable or valid estimate of  $W'$ . Dekerle et al. [10] compared CP to EP using the SRM ergometer in isokinetic mode performed at 60 and 100 rev·min<sup>-1</sup> and, although no significant differences were found, the results suggested that EP overestimates CP. Although WEP did not differ from  $W'$ , Dekerle et al. [10] suggested that care should be taken when using this protocol as it also provided poor reliability. Due to the low levels of agreement, the authors suggested EP may not truly represent CP. In contrast, Tsai [27] reported that the 3-minute all-out test in isokinetic mode using the Lode Excalibur Sport cycle ergometer underestimated CP by approximately 4%. Although it has been suggested that the 3-minute all-out cycling test can estimate CP and  $W'$  against a fixed resistance using the Lode Excalibur Sport, research is less clear when using isokinetic ergometry [10,18,27].

The aim of the present study was to investigate the reliability and validity of the 3-minute all-out test in determining critical power and  $W'$  when performed at a constant cadence (isokinetic mode) and when using a fixed resistance (linear mode). It was hypothesised that both the isokinetic and linear modes would provide a reliable and valid estimate of CP and  $W'$ .

## **Methods**

### **Participants**

Twelve male cyclists (mean  $\pm$  SD: age  $32 \pm 6.6$  years, body mass  $81.6 \pm 8.6$  kg, Maximum Aerobic Power (MAP)  $349 \pm 36$  W,  $\dot{V}O_{2peak}$   $4.4 \pm 0.5$  L $\cdot$ min $^{-1}$ ) provided written informed consent to participate in the study. The study was conducted in accordance with the ethical standards of the International Journal of Sports Medicine [14] and was approved by the host university's ethics committee. Each participant took part in 8 tests, each separated by a minimum of 48 hours. Test 1 was carried out in order to calculate gas exchange threshold (GET), MAP and  $\dot{V}O_{2peak}$  along with providing each participant with a familiarisation trial of the 3-minute all-out cycling test. The remaining 7 tests were carried out to calculate CP and  $W'$  and the estimates EP and WEP. All testing was carried out using an electronically braked cycle ergometer (Excalibur Sport, Lode, The Netherlands). The bike settings for each participant (e.g. seat and bar height) were noted on the first visit to allow replication during all tests. The participants were instructed to avoid heavy exercise in the 24 hours prior to each testing session, to avoid food intake for 3 hours prior to testing and to drink 500 ml of water 2 hours before arriving at the laboratory. Following the measurement of GET, MAP and  $\dot{V}O_{2peak}$ , subsequent tests were carried out in a randomized order. During all testing sessions, strong verbal encouragement was provided; however, no feedback was given regarding elapsed time or power output.

### **GET, MAP and $\dot{V}O_{2peak}$ protocol**

Participants completed an incremental exhaustive ramp test to determine GET, MAP and  $\dot{V}O_{2peak}$ . Participants started at a work rate of 150 W with 20 W $\cdot$ min $^{-1}$  increments [9] until volitional exhaustion.

Breath-by-breath expired air (Oxycon Pro, Viasys, Germany) and heart rate (RCX5, Polar, Finland) were recorded throughout the test with a post-test capillary blood lactate sample (Lactate Pro, Arkray, UK) taken immediately after completion of each test. GET was calculated using the V-slope method [2] with MAP and  $\dot{V}O_{2peak}$  calculated as the highest mean power output and oxygen consumption, respectively, over a 30-second period [18].

### **Original critical power test**

On separate days, each participant completed three tests to exhaustion at 80, 100 and 105% MAP following a standardized 10-minute warm up at 100 W [18]. During each test, participants were instructed to cycle at their preferred cadence for as long as possible. Tests were terminated once cadence dropped by more than 10 rev·min<sup>-1</sup> below the pre-determined preferred cadence for more than 5 seconds. Consistent with Vanhatalo et al. [28] and Karsten et al. [18], CP and W' were calculated using linear regression from the power-1/time,  $P=W'(1/t)+CP$ , mathematical model [32].

### **3-minute all-out cycling tests**

On different days, four tests were carried out to calculate EP and WEP from two separate 3-minute all-out protocols. Two tests were carried out against a fixed resistance (i.e. linear mode) and two using a fixed cadence (i.e. isokinetic mode). The fixed resistance was set using the ergometer's linear mode and in line with the protocol described by Vanhatalo et al. [28]. During the isokinetic tests participants cycled at their preferred cadence for the duration of each trial [18]. In this mode, the participants were unable to cycle faster than the selected cadence and an increase in torque resulted in an increase in resistance. Following a 10-minute warm up at 100 W, all 3-minute tests started with a 30-second period of unloaded cycling at the participant's preferred cadence. During the final 10 seconds of this period the participants were instructed to increase their cadence by 10 rev·min<sup>-1</sup> and, after a countdown, were encouraged to attain peak power in the first 5 seconds of the 3-minute tests. During the linear tests, this was achieved by encouraging the participants to cycle at the highest possible

cadence throughout the test and it was clearly explained that the test should not be paced. During the isokinetic tests, the participants were encouraged to cycle at maximal effort throughout each test. Breath-by-breath analysis and heart rate was measured for all tests to ensure that the participants attained the testing criteria set by Jones et al. [22], i.e. that 1) participants need to be motivated and familiarised with the testing protocol, 2) time-based feedback should not be provided to avoid pacing, 3) participants should be encouraged to maximise cadence throughout the test and 4) attainment of >95% ramp  $\dot{V}O_{2\max}$  with no decremental trend in  $\dot{V}O_2$  observed during the test. A warm down at 50 W was carried out for 5 minutes following each trial with additional time provided if required. All participants were monitored for at least 15 minutes to ensure their safety before leaving the laboratory. For each of the 3-minute tests, EP was calculated as the mean power output over the final 30 seconds and WEP was calculated as the power-time integral above EP.

### **Statistical analyses**

Shapiro-Wilk tests of normality were carried out on all data prior to analysis. The Greenhouse-Geisser procedure was used as a result of the data violating the assumptions of sphericity (Mauchly's Test of Sphericity,  $P < 0.001$ ). Consistent with Karsten et al. [18] and Vanhatalo et al. [28], agreement between CP and EP and between  $W'$  and WEP for both the linear and isokinetic tests was measured using a one-way repeated-measures ANOVA and limits of agreement (LoA) [4]. To adjust for multiple comparisons during the one-way repeated-measures ANOVA, the Bonferroni procedure was used. The reliability between testing sessions was measured using coefficient of variation (CoV), intraclass correlation coefficients (ICC) and Standard Error of Measurement (SEM). Consistent with Karsten et al. [18], the error associated with predicting EP and WEP from linear regression methods was measured using standard error of estimates (SEE). In addition, Pearson's product moment correlation coefficients were carried out to measure relationships. Statistical significance was accepted at  $P < 0.05$  with all data reported as means  $\pm$  SD.

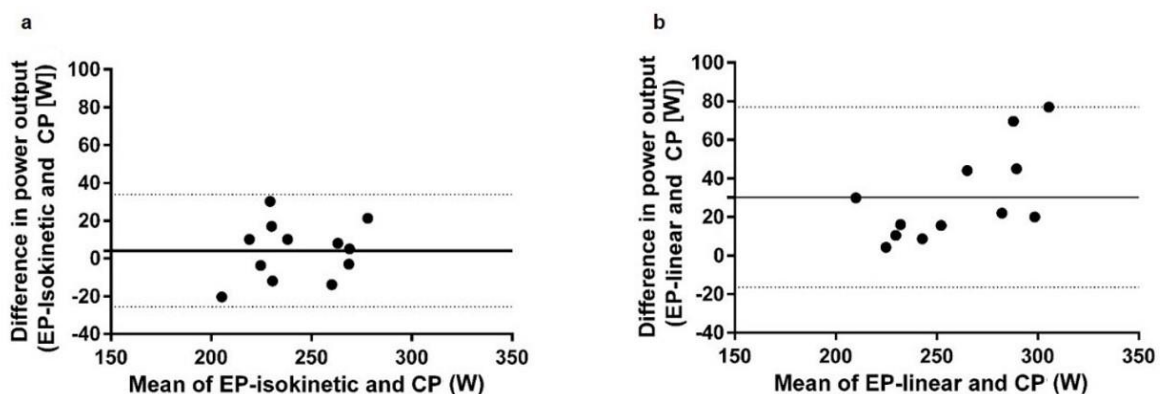
## Results

The mean  $\dot{V}O_{2peak}$  and peak blood lactate for each testing protocol can be found in table 1. Critical power and  $W'$  calculated from the power-1/time mathematical model resulted in an  $R^2$  value of  $0.97 \pm 0.03$ . A one-way repeated-measures ANOVA showed no significant differences between EP-isokinetic and CP ( $240.9 \pm 23.3$  W vs.  $244.9 \pm 26.2$  W,  $P = 1.000$ , 95% LoA of  $4.03 \pm 29.68$  W). There were significant differences between EP-linear and CP ( $275.1 \pm 41.2$  W vs.  $244.9 \pm 26.2$  W,  $P = 0.005$ , 95% LoA of  $30.22 \pm 46.75$  W). The limits of agreement between CP and the EP estimates from the isokinetic and linear tests are shown in figure 1.

**Table 1** Mean values ( $\pm$  SD) for  $\dot{V}O_{2peak}$ , peak blood lactate, CP and  $W'$  observed during each testing session

	$\dot{V}O_{2peak}$ (L·min <sup>-1</sup> )	Peak blood lactate (mmol·L <sup>-1</sup> )	CP/EP (W)	$W'$ /WEP (kJ)
Ramp protocol	$4.4 \pm 0.5$	$11.3 \pm 0.6$	-	-
Original CP protocol	$4.3 \pm 0.5$	$11.5 \pm 2.1$	$244.9 \pm 26.2$	$22.7 \pm 5.6$
3-min all-out test (isokinetic)	$4.5 \pm 0.5$	$12.5 \pm 2.3$	$240.9 \pm 23.3$	$15.6 \pm 5.6^*$
3-min all-out test (linear)	$4.4 \pm 0.4$	$12.8 \pm 2.1$	$275.1 \pm 41.2^*$	$13.5 \pm 4.7^*$

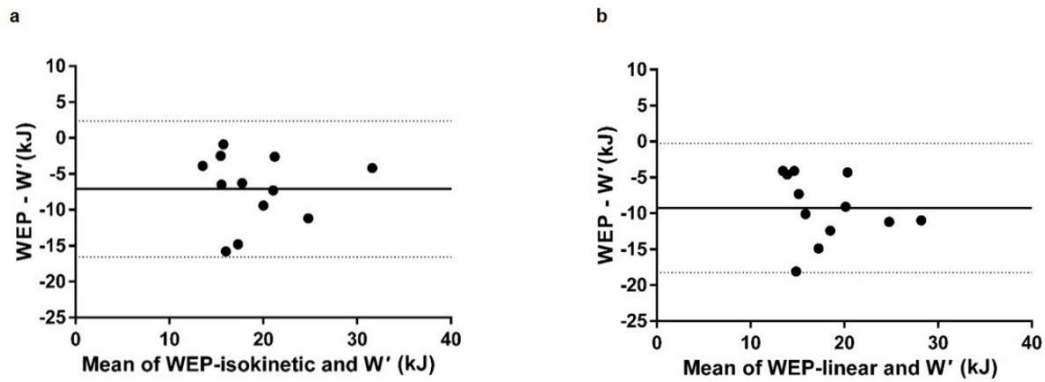
\* Significantly different from the original CP protocol ( $P < 0.005$ ).



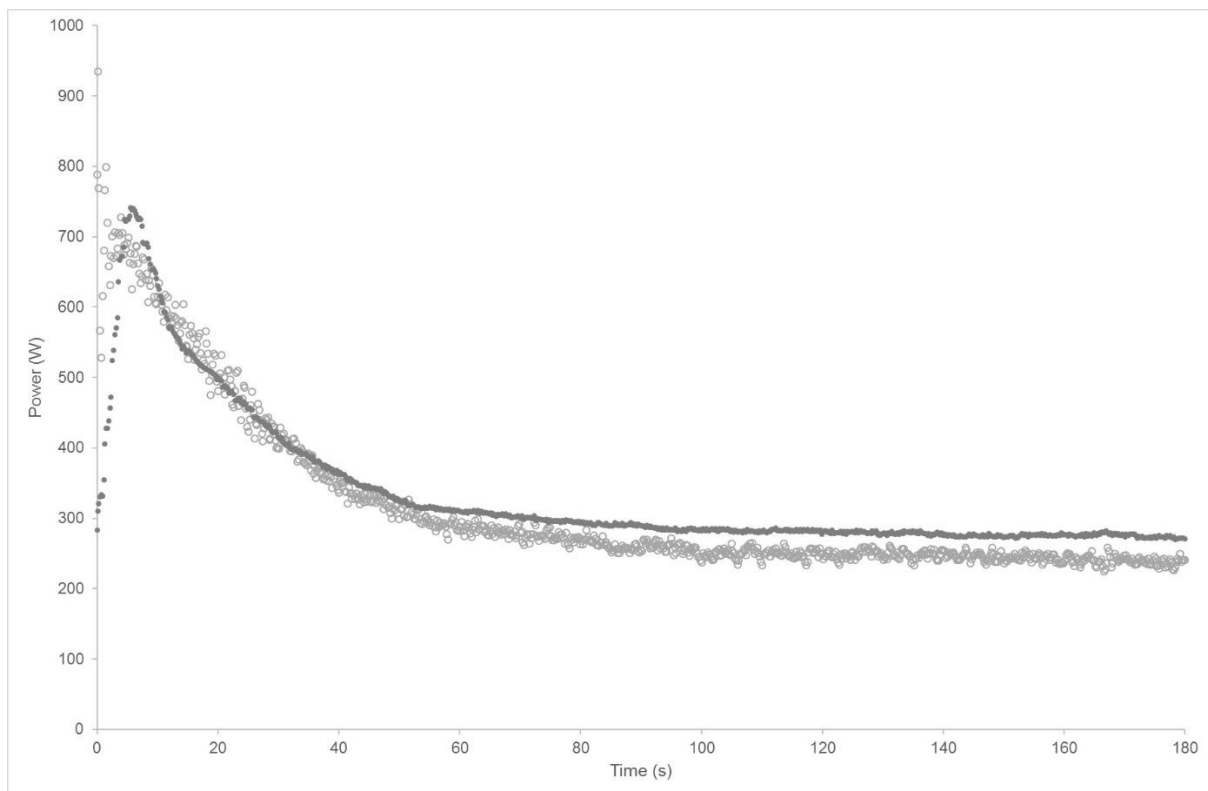
**Figure 1** Bland-Altman plots showing the limits of agreement between EP-isokinetic and CP (a) and EP-linear and CP (b). The solid line represents the mean difference in power output and the dashed line represents the 95% limits of agreement



Significant differences were identified between WEP-isokinetic and  $W'$  ( $15.6 \pm 5.6$  kJ vs.  $22.7 \pm 5.6$  kJ,  $P < 0.001$ , 95% LoA of  $-7.12 \pm 9.47$  kJ) and between WEP-linear and  $W'$  ( $13.5 \pm 4.7$  kJ vs.  $22.7 \pm 5.6$  kJ,  $P < 0.001$ , 95% LoA of  $-9.27 \pm 8.99$  kJ). The limits of agreement between WEP-isokinetic and  $W'$  and between WEP-isokinetic and  $W'$  are illustrated in figure 2.



**Figure 2** Bland-Altman plots of the limits of agreement between WEP-isokinetic and  $W'$  (a) and WEP-isokinetic and  $W'$  (b). The solid line represents the mean difference in power output and the dashed line represents the 95% limits of agreement



**Figure 3** Group mean power profile observed during the 3-minute all-out cycling test in both isokinetic mode (open circles) and linear mode (closed circles)

The standard error of estimates and Pearson’s product moment correlation coefficients between EP-isokinetic and CP, EP-linear and CP, WEP-isokinetic and  $W'$  and WEP-linear and  $W'$  are shown in table 2. Coefficient of variation in EP-isokinetic, EP-linear, WEP-isokinetic and WEP-linear was 1.93%, 1.17%, 8.44% and 5.39%, respectively, between tests 1 and 2. The intraclass correlation coefficient for EP-isokinetic was 0.97 (95% CI = 0.91–0.99),  $P < 0.001$ , EP-linear was 0.99 (95% CI = 0.98–0.99),  $P < 0.001$ , WEP-isokinetic was 0.94 (95% CI = 0.80–0.98),  $P < 0.001$  and WEP-linear was  $r = 0.98$  (95% CI = 0.93–0.99),  $P < 0.001$  (table 3)

**Table 2** Standard error of estimates and Pearson’s product moment correlation coefficients between EP and CP, and WEP and  $W'$  during both isokinetic and linear modes

	<i>R</i>	Isokinetic		<i>R</i>	Linear	
		SEE	SEE %		SEE	SEE %
EP vs. CP	0.82, $P = 0.001$	12.79 W	5.31	0.84, $P = 0.001$	21.35 W	7.76
WEP vs. $W'$	0.63, $P = 0.029$	4.18 kJ	26.81	0.61, $P = 0.034$	3.52 kJ	26.17

**Table 3** Coefficient of variation, intraclass correlation coefficients and standard error of estimate between testing sessions for EP-isokinetic, EP-linear, WEP-isokinetic and WEP-linear

	CoV	ICC ( $\alpha$ )	SEM
EP-isokinetic (1 vs. 2)	1.93%	0.97	5.29 W
EP-linear (1 vs. 2)	1.17%	0.99	3.70 W
WEP-isokinetic (1 vs. 2)	8.44%	0.94	1.90 kJ
WEP-linear (1 vs. 2)	5.39%	0.98	0.83 kJ

## Discussion

The results of the present study suggest that the 3-minute all-out cycling test in isokinetic mode provides a reliable measure of EP and a valid estimate of CP. Although the 3-minute all-out cycling test in linear mode provides a reliable measure of EP, results suggest that the linear mode does not provide a valid estimate of CP. Results also suggest that neither 3-minute test mode provides a reliable

measure of WEP or a valid estimate of  $W'$ , with both the isokinetic and linear mode significantly underestimating  $W'$ .

Karsten et al. [18] found that whilst providing a reliable measure of EP, the 3-minute all-out test carried out in the isokinetic mode overestimated CP by approximately 37 W when using the power-1/time mathematical model. However, Dekerle et al. [10], found that there was no significant difference between EP and CP when the 3-minute all-out test was carried out at 60 and 100 rev·min<sup>-1</sup>. In contrast, Tsai [27] found that EP underestimated CP by approximately 11 W when carried out in isokinetic mode. The results from the present study differ with both Karsten et al. [18] and Tsai [27] with no significant differences observed between EP-isokinetic and CP. The results from the present study also conflict with the research carried out in the linear mode by Vanhatalo et al. [28,29,31]. Where Vanhatalo et al. [28] reported near identical CP and EP, the present study observed significant differences between EP-linear and CP ( $275.1 \pm 41.2$  W vs.  $244.9 \pm 26.2$  W,  $P = 0.004$ ). It would appear that the 3-minute all-out cycling test in isokinetic mode provides a valid estimate of CP; however, the results of this study raises questions regarding the validity of the 3-minute all-out test when carried out against a fixed resistance following the protocol set by Vanhatalo et al. [28]. For both testing modes, it would appear that the reliability of the 3-minute all-out cycling test is good. In line with previous research [18,21], reliability of EP-isokinetic and EP-linear between testing sessions was seen to have a coefficient of variation of less than 5% (1.93% and 1.17% respectively). [Hopkins WG. A new view on statistics. Internet Society for Sport Science (2000). In Internet: <http://www.sportsci.org/resource/stats/>; (Accessed 29 November 2016)]

Data collection during the present study differed to Karsten et al. [18] only with the additional measurement of pulmonary gases during all tests. During all testing sessions of the present study, participants met the criteria of a successful test required by Jones et al. [22]. On only one occasion was a participant required to repeat one of the testing sessions, this the result of a decremental trend in

$\dot{V}O_2$  during the final 30 seconds of one of the 3-minute all-out tests. Without the measurement of pulmonary gases, Karsten et al. [18] were unable to state with certainty if all of the above criteria were met during all of their tests and it could be suggested that the participants in their study may not have exercised at a high enough intensity throughout each test. The physical demands of participating in this study were high, with eight exhaustive testing sessions carried out by each participant. A randomized trial order was carried out to reduce the likelihood of any changes in fitness affecting the results, however it should be acknowledged as a potential limitation and a factor which may have affected the calculation of both CP and  $W'$ . Another limitation of this study was the lack of a verification procedure following the calculation of CP [8].

A key result of this study was the significant overestimation of EP when the 3-minute all-out cycling test was carried out in the linear mode, especially when compared to the original research by Vanhatalo et al. [28] who found EP and CP to be almost identical. These differences could be explained by the cadence selected in order to calculate the linear factor for each participant with previous research suggesting that EP is sensitive to small changes in cadence [30]. In order to calculate the linear factor, each participant was asked for their preferred cadence and it was noted that a number of participants stated a range between 5–10 rev·min<sup>-1</sup>. This cadence selection could help to explain why differences are noted within the literature in both isokinetic and linear modes and it is possible that the cadences selected for some participants was too low. Typically, a trained cyclist will state that their preferred cadence is between 90–100 rev·min<sup>-1</sup> but this will depend on the demands of the ride, for example during a time-trial or mountain stage [1]. A study by Vanhatalo et al. [30] found that EP can be reduced by approximately 10 W when using a cadence 10 rev·min<sup>-1</sup> above the participant's preferred cadence. Similarly, Dekerle et al. [10] evaluated the 3-minute all-out test in isokinetic mode at both 60 and 100 rev·min<sup>-1</sup> and reported a 14% lower EP upon the adoption of the higher cadence. These reductions in EP were attributed to the fact that fast twitch muscle fibres are more susceptible to fatigue when pedalling at higher cadences [10]. This results in

a fast decline in power output over the duration of the test, which in turn produces a lower EP during the final 30 seconds. In order to overcome this potential limitation of the 3-minute all-out cycling test when carried out against fixed resistance, alternative procedures have been suggested [8,11]. These include the use of a percentage of body mass value being used to determine the testing resistance with positive results seen. Although the results from the present study conclude that the 3-minute all-out test against a fixed resistance does not provide a valid estimation of CP, it is possible that this is due to the methods used to calculate this resistance. It is suggested that the original method for calculating this resistance (e.g. preferred cadence) is susceptible to error which may lead to inaccurate testing results. A more recent study by Karsten et al [19] concluded that CP can be determined during a single session of 90 minutes. However, results also found that this testing protocol does not provide valid estimates of  $W'$  and more research is required if a single session test protocol can be used as a valid method in the determination of both CP and  $W'$ .

The estimates of  $W'$  were significantly lower for both isokinetic (-7.1 kJ) and linear modes (-9.2 kJ). These results suggest that neither testing mode provides a reliable measure of WEP or a valid estimate of  $W'$ . Although these differences were larger than shown in previous studies, several authors have reported that the 3-minute all-out test carried out in both linear and isokinetic modes underestimates  $W'$  [18, 28]. Previous studies have also suggested that with significant variations in WEP observed between testing sessions, this parameter lacks sensitivity and is in effect, meaningless. [10, 21]. Vanhatalo et al. [28] suggested that these results may be due to the differences in power measurement between the 3-minute all-out cycling test and the constant-power tests when using the Lode Excalibur Sport. They explain that during the first 10 seconds of the 3-minute all-out cycling test there is acceleration of the Lode's flywheel when performed in the linear mode. However, this acceleration is absent during the constant-power trials used to calculate  $W'$  using the original protocol. Vanhatalo et al. [28] suggest the use of the isokinetic mode or SRM cranks to overcome this problem as they are unaffected by flywheel inertia. However, the present study found that WEP was

significantly lower than  $W'$  when tested in isokinetic mode, supporting the findings of Karsten et al. [18]. It might be suggested that a 3-minute all-out cycling test is not long enough to fully deplete  $W'$  in all individuals. Therefore, more research focusing on the finite work capacity during exhaustive exercise is recommended using trained cyclists. It should be noted that the research by Vanhatalo et al. [28,29,30] was carried out using participants from a mixture of athletic backgrounds and that they may not have all been fully accustomed to all-out cycling. Before the 3-minute all-out cycling test can be used with confidence to estimate CP, additional research is required into the effect cadence has on setting the test resistance.

## **Conclusion**

The main finding of this study suggests that the 3-minute all-out cycling test performed in isokinetic mode is reliable and can also be used to estimate critical power. It would appear that although reliable, the 3-minute all-out cycling test performed in linear mode does not provide a valid estimate of CP when following the methods used by Vanhatalo et al. [28]. It is suggested that care should be taken when selecting a testing mode to complete the 3-minute all out cycling test. Furthermore, although the 3-minute all-out cycling test is successfully used within applied research, the results of the present study highlight that there are potential causes for concern with the protocol used. It is suggested that future research focuses on the methods used to set the fixed resistance and to follow on from the work of Dicks et al [11]. Results also suggest that neither testing mode provides a reliable or valid estimate of  $W'$ , which would appear to be more comparable to previous studies. Cadence selection, the duration of the test and also the testing ergometer and mode may all affect the estimates of CP and  $W'$ .

## **Acknowledgements**

The authors would like to thank Dr Helen Thomas from Southampton Solent University for her assistance during this study. The authors would also like to thank all the participants who volunteered their time to take part.

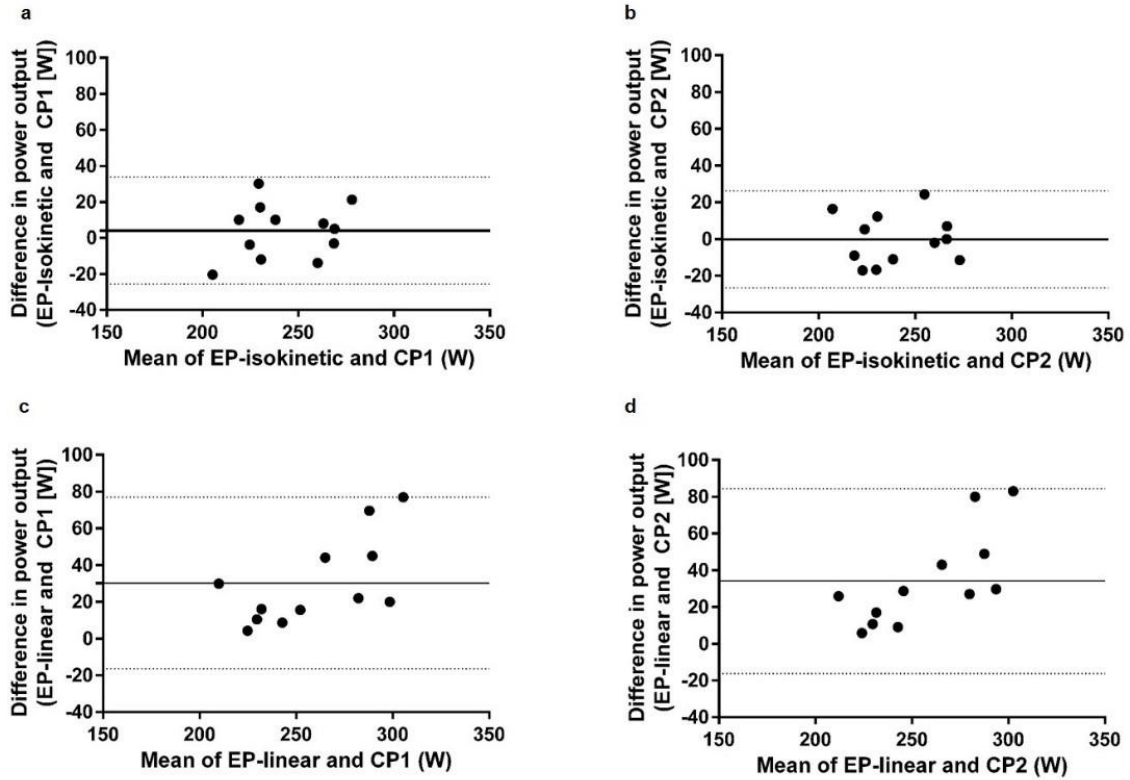
## References

1. *Abbiss CR, Peiffer JJ, Laursen PB.* Optimal cadence selection during cycling. *Int Sport J* 2009; 10: 1–15.
2. *Beaver W, Karlman W, Whipp BJ.* A new method for detecting anaerobic threshold by gas exchange. *J Appl Physiol* 1986; 60: 2020–2027
3. *Bergstrom HC, Housh TJ, Zuniga JM, Camic CL, Traylor DA, Schmidt RJ, Johnson GO.* A New Single Work Bout Test to Estimate Critical Power and Anaerobic Work Capacity. *J Strength Cond Res* 2012; 26: 656–663
4. *Bland JM, Altman DG.* Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986; 1: 307–310
5. *Brickley G, Deckerle J, Hammend AJ, Pringle J, Carter H.* Assessment of Maximal Aerobic Power and Critical Power in a Single 90-s Isokinetic All-Out Cycling Test. *Int J Sports Med* 2007; 28: 414–419
6. *Burnley M, Doust JH, Vanhatalo A.* A 3-min All-Out Test to Determine Peak Oxygen Uptake and the Maximal Steady State. *Med Sci Sports Exerc* 2006; 38: 1995–2003
7. *Carnevale TJ, Gaesser GA.* Effects of pedalling speed on the power duration relationship for high-intensity exercise. *Med Sci Sports Exerc* 1991; 23: 242–246
8. *Clark IE, Murray SR, Pettitt RW.* Alternative procedures for the 3-min all-out exercise test. *J Strength Cond Res* 2013; 27: 2444–48
9. *Davis JA, Whipp BJ, Lamarra N, Huntsman DJ, Frank NH, Wasserman L.* Effect of ramp slope on determination of aerobic parameters from the ramp exercise test. *Med Sci Sports Exerc* 1982; 14: 339–43
10. *Deckerle J, Barstow TJ, Regan, L, Carter, H.* The critical power concept in all-out isokinetic exercise. *J Sci Med Sports* 2013; 1–5
11. *Dicks ND, Jamnick NA, Murray SR, Pettitt RW.* Load Determination for the 3-min All-Out Exercise Test for Cycle Ergometry. *Int J Sports Physiol Perform* 2016; 11: 197–203

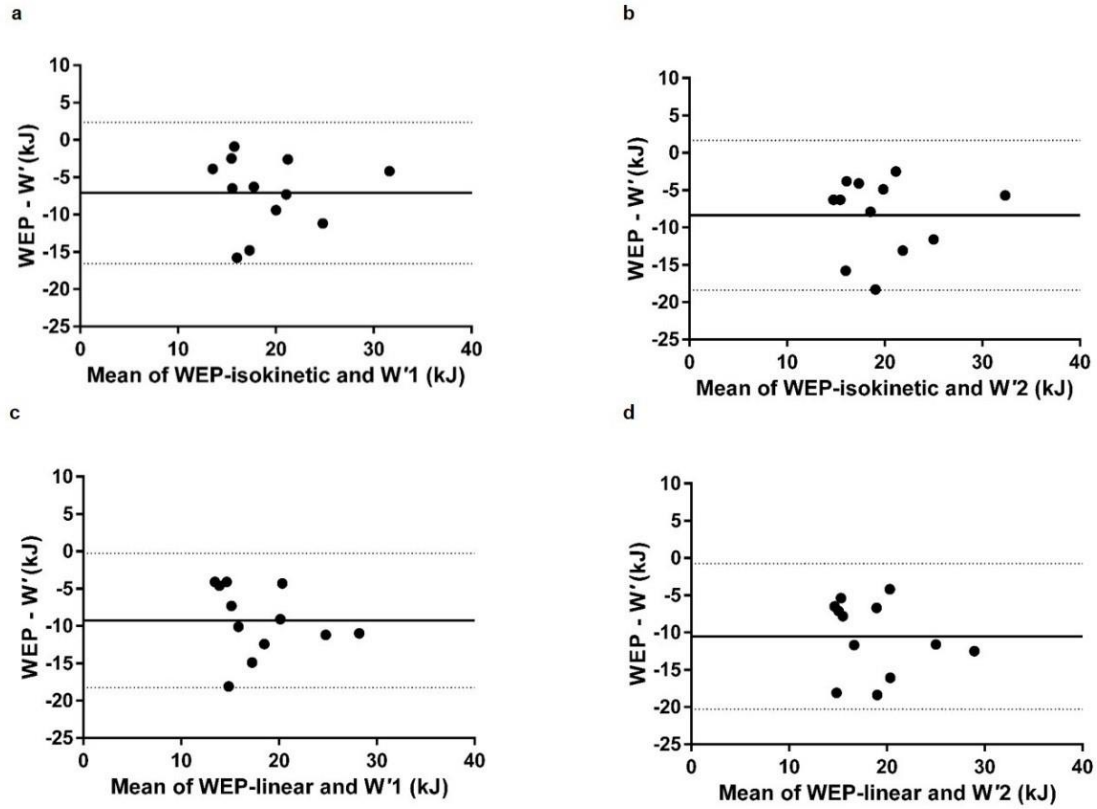
12. *Faude O, Kindermann W, Meyer T.* Lactate Threshold Concepts – How Valid are They? *Sports Med* 2009; 39: 469–490
13. *Gaesser GA, Wilson LA.* Effects of continuous and interval training on the parameters of the power-endurance time relationship for high intensity exercise. *Int J Sports Med* 1988; 9: 417–421
14. *Harriss DJ, Atkinson G.* Update – Ethical standards in sport and exercise science research. *Int J Sports Med* 2015; 36: 1121–1124
15. *Hill DW.* The critical power concept. A review. *Sports Med* 1993; 16: 237–254
16. *Hopker J, Jobson S.* *Performance Cycling: The Science of Success* 2013. Bloomsbury: UK
17. *Housh DJ, Housh TJ, Bauge SM.* The accuracy of the critical power test for predicting time to exhaustion during cycle ergometry. *Ergonomics* 1989; 8: 997–1004
18. *Karsten B, Jobson SA, Hopker J, Passfield L, Beedle C.* The 3-min Test Does not Provide a Valid Measure of Critical Power Using the SRM Isokinetic Mode. *Int J Sports Med* 2014; 35: 304–309
19. *Karsten B, Hopker J, Jobson SA, Baker J, Petrigna L, Klose A, Beedie C.* Comparison of inter-trial recovery times for the determination of critical power and  $W'$  in cycling. *J. Sports Sci* 2016; 17: 1–6
20. *Jenkins D, Quigley BM.* Blood lactate in trained cyclists during cycle ergometry at critical power. *Eur J Appl Physiol* 1990; 61: 278–283
21. *Johnson TM, Sexton PJ, Placek AM, Murray SR, Pettitt RW.* Reliability Analysis of the 3-min All-Out Exercise Test for Cycle Ergometry, *Med Sci Sports Exerc* 2011; 43: 2375–2380
22. *Jones AM, Vanhatalo A, Burnley M, Morton RH, Poole D.* Critical Power: Implications for Determination of  $VO_{2max}$  and Exercise Tolerance. *Med Sci Sports Exerc* 2010; 44: 1876–1890
23. *McClave SA, LeBlanc M, Hawkins SA.* Sustainability of Critical Power Determined By A 3-Minutes All-Out Test in Elite Cyclists, *J Strength Cond Res* 2011; 25: 3093–3098
24. *Paton CD, Hopkins WG.* Tests of Cycling Performance. *Sport Med* 2001; 31: 489–496.
25. *Smith JC, Hill DW.* Stability of parameter estimates derived from the power/time relationship. *J Appl Physiol* 1993; 18: 43–47



26. *Triska C, Tschan H, Tazreiter G, Nimmerichter A.* Critical Power in Laboratory and Field Conditions Using Single-visit Maximal Effort Trials. *Int J Sports Med* 2015; 36: 1063–1068
27. *Tsai M.* Revisiting the Power-Duration Relationship and Developing Alternative Protocols to Estimate Critical Power Parameters 2015; Ph.D thesis, University of Toronto
28. *Vanhatalo A, Doust JH, Burnley M.* Determination of critical power using a 3-min all-out cycling test. *Med Sci Sports Exerc* 2007; 39: 548–555
29. *Vanhatalo A, Doust JH, Burnley M.* A 3-min all-out cycling test is sensitive to a change in critical power. *Med Sci Sports Exerc* 2008; 40: 1693–1699
30. *Vanhatalo A, Doust JH, Burnley M.* Robustness of a 3 min all-out cycling test to manipulations of power profile and cadence in humans. *Exp Physiol* 2008; 93: 383–390
31. *Vanhatalo A, Jones AM, Burnley M.* Application of Critical Power in Sport, *International J Sports Physiol Perf* 2011; 6: 128–136
32. *Whipp BJ, Huntsman DJ, Stoner N, Lamarra N, Wasserman KA.* A constant which determines the duration of tolerance to high-intensity work, *Fed Proc* 1982; 41: 1591



**Figure 1** Bland-Altman plots showing the limits of agreement between EP-isokinetic and CP1 (a), EP-isokinetic and CP2 (b), EP-linear and CP1 (c) and EP-linear and CP2 (d). The solid line represents the mean difference in power output and the dashed line represents the 95% limits of agreement.



**Figure 2** Bland-Altman plots of the limits of agreement between WEP-isokinetic and W'1 (a), WEP-isokinetic and W'2 (b), WEP-linear and W'1 (c) and WEP-linear and W'2 (d). The solid line represents the mean difference in power output and the dashed line represents the 95% limits of agreement.

**Table 1** Standard error of estimates and intraclass correlation coefficients between EP and CP, and WEP and  $W'$  during both isokinetic and linear modes.

	Isokinetic Mode		Linear Mode	
	ICC	SEE (W)	ICC	SEE (kJ)
EP vs. CP1	$r = 0.82, P = 0.001$	12.79	$r = 0.84, P = 0.001$	21.35
EP vs. CP2	$r = 0.83, P = 0.001$	12.41	$r = 0.83, P = 0.001$	22.18
WEP vs. $W'1$	$r = 0.63, P = 0.029$	4.18	$r = 0.61, P = 0.034$	3.52
WEP vs. $W'2$	$r = 0.58, P = 0.048$	4.38	$r = 0.54, P = 0.730$	3.76