The 3-minute all-out cycling test is sensitive to changes in cadence using the Lode Excalibur Sport Ergometer

James Wright[a]*, Stewart Bruce-Low[a] and Simon A. Jobson[b]

[a]*School of Sport, Health and Social Science, Southampton Solent Unviersity, Southampton, UK;* [b]*Department of Sport & Exercise, University of Winchester, Winchester, UK*

Mr James Wright (corresponding author)
Southampton Solent University, School of Sport, Health and Social Science
East Park Terrace, Hampshire, SO14 0YN
E: james.wright@solent.ac.uk T: 023 8031 3955

Prof Simon Jobson
University of Winchester, Department of Sport & Exercise
Sparkford Road, Hampshire, SO22 4NR
E: simon.jobson@winchester.ac.uk

Prof Stewart Bruce-Low
Southampton Solent University, School of Sport, Health and Social Science
East Park Terrace, Hampshire, SO14 0YN
E: stewart.bruce-low@outlook.com

Keywords: **Exercise Testing, Training Zones, Fatigue**

Abstract

This study investigated the effect cadence has on the estimation of critical power (CP) and the finite work capacity (*W′*) during the 3-minute all-out cycling test. Ten participants completed 8 tests: 1) an incremental test to calculate gas exchange threshold (GET), maximal aerobic power (MAP) and peak oxygen uptake ($\dot{V}O_{2peak}$), 2–4) three time-trial to exhaustion tests at 80, 100 and 105% MAP to calculate CP and *W′*, 5–7) four 3-minute all-out tests to calculate end power (EP) and work done above EP (WEP) using cadences ranging from preferred −5 to preferred +10 rev·min^{-1} to set the fixed resistance. Significant differences were seen between CP and EP-preferred (267.5 ± 22.6 W vs. 296.6 ± 26.1 W, $P < 0.001$), CP and EP−5 (267.5 ± 22.6 W vs. 303.6 ± 24.0 W, $P < 0.001$) and between CP and EP+5 (267.5 ± 22.6 W vs. 290.0 ± 28.0 W, $P = 0.002$). No significant differences were seen between CP and EP+10 (267.5 ± 22.6 W vs. 278.1 ± 30.9 W, $P = 0.331$). Significant differences were seen between *W′* and WEP at all tested fixed resistances. EP is reduced when cycling at higher than preferred cadences, providing better estimates of CP.

Introduction

Critical power (CP) was originally described as the highest rate of aerobic metabolism that can be sustained without fatigue (Monod and Scherrer, 1965). However, more recently, Burnley, Vanhatalo and Jones (2012), have demonstrated that peripheral fatigue does develop below critical power. This concept has been investigated in cycling for over 30 years and it is suggested that CP defines the boundary between the heavy and severe exercise intensity domains within an error of approximately 5% (Poole et al., 2016). The CP test allows the determination of two parameters: an aerobic component, which is rate- but not capacity-limited (CP), and an anaerobic component, which is capacity- but not rate-limited (*W′*) (Jones, Vanhatalo, Burnley, Morton & Poole, 2010). Although CP and *W′* can provide coaches with information to inform athlete training, a typical testing session requires 3–8 time-to-exhaustion (TTE) cycling tests, which is often overly onerous on the athlete (Abbiss, Peiffer & Laursen, 2009; Gaesser and Wilson 1988; Jenkins and Quigley, 1990; Smith and Hill, 1993).

The impractical nature of the original CP test protocol has led to the development of the 3-minute all-out cycling test which aims to provide estimations of CP and *W′* (Vanhatalo, Doust & Burnley, 2007). Cycling against a fixed resistance, the 3-minute all-out test aims to fully deplete *W′* within the first 150 seconds, resulting in a plateau of power output in the final 30 seconds of the test. The final power observed from this test, end power (EP), and the work above EP (WEP), should in theory be the same as CP and *W′* calculated from the original testing protocol. Vanhatalo, Doust and Burnley (2007) found that the 3-minute all-out cycling test provided near identical estimations of CP and similar, albeit slightly lower, estimations of *W′*. However, more recent studies have found that EP overestimates CP by approximately 5–12%, with WEP significantly underestimating *W′* (Dekerle, Barstow, Regan & Carter, 2014; Karsten, Jobson, Hopker, Passfield & Beedle, 2014; Wright, Bruce-Low & Jobson, 2017). During the studies by Dekerle et al. (2014) and Karsten et al. (2014), the 3-minute all-out cycling test was carried out using a fixed cadence of between 60–100 rev·min^{-1} (isokinetic mode) rather than against a fixed resistance (linear mode) as used by Vanhatalo et al. (2007). This difference in testing mode may help to explain why both Dekerle et al. (2014) and Karsten et al. (2014) found that the 3-minute all-out test overestimates CP. However, a more recent study by Wright et al. (2017) evaluated CP using both isokinetic and linear modes, with results suggesting that EP determined from the linear mode significantly overestimated CP. Results also suggested that EP determined from the isokinetic mode provided a closer estimation of CP. The results from the studies above would suggest that the differences observed between CP and EP are not necessarily attributable to the testing mode used during the 3-minute all-out cycling test.

Previous research has demonstrated that critical power is sensitive to changes in cadence when calculated from multiple TTE tests. Barker, Poole, Noble and Barstow (2006) found that critical power is reduced by approximately 18 W when the TTE tests were performed at 100 rev·min^{-1} compared to 60 rev·min^{-1}. It has also been demonstrated that the 3-minute all-out cycling test is sensitive to small changes in the cadence used to set the ergometer's fixed resistance (Vanhatalo, Doust & Burnley, 2008). When the test protocol is carried out against a fixed resistance, it is important to ensure that this resistance is individualised for each athlete. The Lode Excalibur Sport ergometer, as used by Vanhatalo et al. (2007), uses the following equation to set the pedalling resistance: linear factor = power/preferred cadence^2. Burnley et al.

(2006) suggested that power should correspond to the power output midway between gas exchange threshold (GET) and $\dot{V}O_{2peak}$ (50%Δ). The linear factor is very sensitive to changes in cadence due to the squared function within the equation. It is therefore important to ensure that a correct cadence is selected for each participant, especially when the term 'preferred cadence' is ambiguous. Vanhatalo et al. (2008) demonstrated that EP is sensitive to changes in the cadence used to set the linear factor. Their findings suggested that, although unaffected by selecting a lower cadence, EP was reduced by approximately 10 W when using a cadence 10 rev·min^{-1} above preferred cadence. It was also found that WEP was significantly higher on the adoption of a lower cadence and lower when using a higher cadence. Dekerle et al. (2014) also found that cadence selection affected EP when carried out in isokinetic mode, with a significantly lower EP observed when tested at 100 rev·min^{-1} compared to 60 rev·min^{-1}. In contrast to Vanhatalo et al. (2008), Dekerle et al. (2014) found that WEP was significantly increased when tested at a higher cadence. In a similar study, deLucas et al. (2014) found a significant reduction in EP on the adoption of a higher cadence (100 vs. 60 rev·min^{-1}) but no differences in WEP were observed between cadences. The results from these studies highlight the importance of selecting the correct cadence before carrying out the 3-minute all-out cycling test.

The aim of the present study was to investigate the effect of cadence on the determination of EP and WEP from a 3-minute all-out cycling test. It was hypothesised that higher cadences would result in a reduction in both EP and WEP.

Methods

Participants

Ten trained (de Pauw et al., 2013) male cyclists (mean ± SD: age 30 ± 5 years, body mass 78.6 ± 6.6 kg, maximum aerobic power (MAP) 368 ± 29 W, $\dot{V}O_{2peak}$ 4.7 ± 0.4 $L \cdot min^{-1}$) volunteered to take part in this study. All participants provided written informed consent and a health screening (PARQ, resting blood pressure, 12-lead ECG) was carried out prior to testing. The study was conducted in accordance with the Declaration of Helsinki and was approved by the host university's ethics committee.

Participants took part in 8 tests to calculate GET, MAP, $\dot{V}O_{2peak}$, CP, W' and the estimates EP and WEP, with each testing session separated by a minimum of 48 hours. Other than test one, for determination of GET, $\dot{V}O_{2peak}$ and MAP, all tests were carried out in a randomized order. All tests were carried out using an electronically braked cycle ergometer (Excalibur Sport, Lode, The Netherlands), with the participant's own shoes and pedals used. The bike settings for each participant (e.g. seat and bar height) were noted on the first visit to ensure that they could be replicated during subsequent testing sessions. Prior to each testing session, participants were instructed to avoid heavy exercise for 24 hours and food intake for 2 hours. Participants were also instructed to drink 500 ml of water 2 hours prior to testing. Strong verbal encouragement was provided during each test but no feedback regarding heart rate, power output or time was provided.

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

Starting at 150 W, each participant completed a maximal incremental ramp test (20 $W \cdot min^{-1}$) to calculate GET, MAP and $\dot{V}O_{2peak}$ (Davis et al., 1982). Throughout the test, breath-by-breath expired air (MasterScreen CPX, Jaeger, Germany) and heart rate (RCX5, Polar, Finland) were recorded at 5-second intervals. On completion of the test, a capillary blood lactate sample (Biosen C-line, EKF Diagnostics, Germany) was taken from the fingertip. GET was calculated using the V-slope method outlined by Beaver, Karlman and Whipp (1986), MAP was calculated as the highest 30-second mean power output and $\dot{V}O_{2peak}$ as the highest 30-second average in $\dot{V}O_2$ (Robergs, Dwyer & Astorino, 2010; Karsten et al. 2014).

Original critical power test

In order to calculate CP and *W′*, each participant completed three separate TTE tests at 80, 100 and 105% MAP (Monod & Scherrer, 1965; Karsten et al., 2014). Following a 10-minute warm up at 100 W, each participant was instructed to cycle at their preferred cadence until volitional exhaustion with heart rate and $\dot{V}O_2$ measured throughout. Each test was terminated when the cadence dropped by more than 10 rev·min^{-1} below the participant's preferred cadence. Consistent with Vanhatalo et al. (2007) and Karsten et al. (2014), CP and *W′* were calculated using linear regression from the power-1/time, P = *W′*(1/t) + CP mathematical model.

3-minute all-out cycling tests

On separate days, EP and WEP were also calculated from four 3-minute all-out cycling tests. All participants had experience of the 3-minute all-out cycling test from a separate study and had completed a minimum of 4 tests in the previous 12 months. For each test, a fixed resistance was used in line with the protocol described by Vanhatalo et al. (2007) and using the following equation: resistance = 50%Δ/preferred cadence^2. Prior to testing, each participant was asked to self-select their preferred cadence and this was used to set the resistance for each test 1) participant's preferred cadence (EP-preferred and WEP-preferred), 2) preferred cadence −5 rev·min^{-1} (EP−5 and WEP−5),

3) preferred cadence +5 rev·min^{-1} (EP+5 and WEP+5) and 4) preferred cadence +10 rev·min^{-1} (EP+10 and WEP+10). Prior to each test, participants were required to complete a standardized 10-minute warm up at 100 W. Each 3-minute all-out test started with an unloaded period of cycling for 30 seconds with participants instructed to increase their cadence to approximately 110 rev·min^{-1} in the final 10 seconds. Following a countdown, participants were instructed to cycle maximally from a seated position and were encouraged to reach peak power output within the first 5 seconds of the 3-minute tests. It was clearly explained that maximal exertion should be given throughout the test. Heart rate and $\dot{V}O_2$ were measured throughout each test with a post-test capillary blood lactate sample taken immediately upon completion. Participants were required to carry out a 5-minute warm down at 50 W to reduce the chances of syncope or nausea with all participants closely monitored for at least 15 minutes after each test.

Statistical analyses

Shapiro-Wilk tests of normality were carried out on all data prior to analysis. A one-way repeated-measures ANOVA, limits of agreement (LoA) and correlation coefficients were used to compare the agreement between CP with EP and W' with WEP at each cadence. During the one-way repeated-measures ANOVA, the Bonferroni correction was used to adjust for multiple comparisons. A one-way repeated-measures ANOVA was also used to compare EP and WEP between testing sessions. Effect sizes (ES) were also calculated using Cohen's *d*; trivial (<0.19), small (0.20–0.49), medium (0.50–0.79) and large (>0.80) (Cumming, 2014). The error associated with predicting EP and WEP from linear regression methods was measured using standard error of estimates (SEE). All data are reported as mean ± SD with statistical significance accepted at $P < 0.05$.

Results

Comparisons between $\dot{V}O_{2peak}$, peak power, EP, peak cadence, end cadence and WEP during each 3-minute all-out test are displayed in table 1. The mean cadences observed during the incremental ramp test and the three TTE tests can be found in table 2. A one-way repeated-measures ANOVA showed significant differences between CP and EP-preferred (268 ± 23 W vs. 297 ± 26 W, $P < 0.001$, 95% LoA of 30 ± 21 W, ES = 1.18), CP and EP−5 (268 ± 23 W vs. 304 ± 24 W, $P < 0.001$, 95% LoA of 36 ± 23 W, ES = 1.53) and between CP and EP+5 (268 ± 23 W vs. 290 ± 28 W, $P = 0.002$, 95% LoA of 23 ± 23 W, ES = 0.86). At the highest cadence, results showed no significant difference between CP and EP+10 (268 ± 23 W vs. 278 ± 31 W, $P = 0.331$, 95% LoA of 11 ± 26 W, ES = 0.37) (Figure 1).

****Table 1 near here****

****Figure 1 near here****

Significant differences were seen between W' and WEP-preferred (20.5 ± 5.1 kJ vs. 11.2 ± 4.5 kJ, $P < 0.001$, 95% LoA of -8.6 ± 10.1 kJ, ES = 1.93), W' and WEP−5 (20.5 ± 5.1 kJ vs. 12.6 ± 4.0 kJ, $P = 0.017$, 95% LoA of -7.7 ± 10.8 kJ, ES = 4.0), W' and WEP+5 (20.5 ± 5.1 kJ vs. 11.0 ± 4.4 kJ, $P = 0.003$, 95% LoA of -9.4 ± 10.4 kJ, ES = 1.99) and between W' and WEP+10 (20.5 ± 5.1 kJ vs. 10.9 ± 4.8 kJ, $P = 0.012$, 95% LoA of -8.9 ± 11.8 kJ, ES = 1.94) (Figure 2).

****Figure 2 near here****

The SEE and correlation coefficients between CP with EP and between *W′* with WEP at each cadence are shown in table 2.

Results from a one-way repeated-measures ANOVA showed no significant differences between EP-preferred and EP−5 (297 ± 26 vs. 304 ± 24 W, $P = 0.173$) or between EP-preferred and EP+5 (297 ± 26 vs. 290 ± 28 W, $P = 0.237$); however, significant differences were seen between EP-preferred and EP+10 (297 ± 28 vs. 278 ± 31 W, $P = 0.001$). It should also be noted that significant differences were seen between EP+10 and all other cadences ($P < 0.05$). No significant differences were found between WEP-preferred and WEP−5 (11.2 ± 4.5 vs. 12.6 ± 4.0 kJ, $P = 0.934$), WEP+5 (11.2 ± 4.5 vs. 11.0 ± 4.4 kJ, $P = 1.000$) or with WEP+10 (11.2 ± 4.5 vs. 10.9 ± 4.8 kJ, $P = 1.000$). Furthermore, no significant differences were seen between any of the cadences ($P > 0.05$). Oxygen uptake during the 3-minute all-out cycling test is highlighted in figure 3 and demonstrates how 95% ramp test $\dot{V}O_{2peak}$ was attained within the first 90 seconds and then maintained for the duration of the test in line with the recommendations set by Jones et al. (2010).

****Figure 3 near here****

****Table 2 near here****

Table 3 highlights the mean cadence, $\dot{V}O_{2peak}$ and time to exhaustion during each testing session. No significant differences were seen between the peak oxygen uptake observed during the ramp test and the 80% MAP TTE (4.8 ± 0.4 vs. 4.6 ± 0.4 $L\cdot min^{-1}$, *P* = 0.820), 100% MAP TTE (4.8 ± 0.4 vs. 4.5 ± 0.6 $L\cdot min^{-1}$, *P* = 1.000) or 105% MAP TTE (4.8 ± 0.4 vs. 4.6 ± 0.5 $L\cdot min^{-1}$, *P* = 1.000) with 95% ramp test $\dot{V}O_{2peak}$ observed for all TTE conditions. The R-squared value for the 1/time mathematical model ranged from 0.970–1.000 for all participants with standard error values of 0.3–15.8 W for CP and 0.6–4.5 kJ for *W′* observed.

****Table 3 near here****

Discussion

The results of this study suggest that EP calculated from the 3-minute all-out cycling test is affected by the cadence used to set the fixed resistance, with a reduction in EP observed at higher cadences. Results also suggest that selecting a cadence 10 $rev\cdot min^{-1}$ above preferred cadence provides the closest estimation of CP, with EP-preferred, EP−5 and EP+5 significantly overestimating CP. Additionally, the results suggest that WEP is unaffected by cadence and that *W′* is significantly underestimated at all cadences tested. These results highlight the importance of selecting the correct cadence when setting the fixed resistance prior to undertaking the 3-minute all-out cycling test.

The 3-minute all-out cycling test has been extensively investigated (Dekerle et al., 2014; deLucas et al. 2014; Dicks, Jamnick, Murray & Pettitt, 2016; Francis, Quinn, Amann & LaRoche, 2010; Johnson, Sexton, Placek, Murray & Pettitt, 2011; Waldron, Gray, Furlan & Murphy, 2016); however, some recent studies have found that EP overestimates CP (Bergstrom et al., 2014; Karsten et al., 2014; Wright et al., 2017). These studies raise questions about the protocols used when performing the 3-minute all-out cycling test. Concerns about the 3-minute all-out test were also raised by Mattioni Maturana et al. (2016). Although the mean difference between CP and EP were not significantly different (253 ± 44 W vs. 250 ± 51 W), the authors concluded that care should be taken due to the wide limits of agreement observed from the Bland-Altman plots. The original research by Vanhatalo et al. (2007) concluded that the 3-minute all-out test provided a reliable measure of EP and WEP, and an almost identical estimation of CP. However, further research found that EP is reduced by approximately 10 W upon the selection of a higher cadence (preferred +10 rev·min^{-1}) but that it is unaffected when tested at a slightly lower cadence (preferred −5 rev·min^{-1}) (Vanhatalo et al. 2008). The results of the present study support these findings, although slightly larger reductions in EP of approximately 20 W were observed at the highest cadence (+10 rev·min^{-1}). Results also suggest that WEP is less sensitive and remains consistent across cadences. These results are supported by those found by Vanhatalo et al. (2008) and Chidnok et al. (2013) who reported that WEP was unaffected by pacing during a 3-minute all-out cycling test. The effect of cadence on EP and WEP has also been investigated when using the isokinetic ergometer mode, with results showing that EP is reduced upon the adoption of a higher cadence (Dekerle et al., 2014; deLucas et al., 2014). Although slightly larger differences of approximately 30–37 W were seen between conditions when tested in isokinetic mode, it should be noted that a greater range in cadences were used (60–100 rev·min^{-1}) in the studies by Dekerle et al. (2014) and deLucas et al. (2014).

With results from the present study demonstrating that EP is reduced at higher cadences, the importance of selecting the correct cadence when performing the 3-minute all-out cycling test is highlighted. It could be assumed that the preferred cadences provided by each participant in the present study were not high enough to elicit similar results to those reported previously (Vanhatalo et al., 2007; Vanhatalo et al., 2008). It can be seen from table 2 that the participants naturally chose a higher cadence for the shorter, and higher power output TTE tests (89.5 ± 4.6 rev·min^{-1} at 80% MAP compared to 96.2 ± 3.4 rev·min^{-1} at 105% MAP) differing from their self-selected preferred cadence of 91.0 ± 1.6 rev·min^{-1}. Abbiss et al. (2009) suggested that, for ultra-endurance events, a cadence of between 70–90 rev·min^{-1} may be optimal due to the reduced energy cost and increased cycling economy observed at lower cadences. However, for endurance events and short duration sprint events, cadences of between 90–100 and 110 rev·min^{-1}, respectively, may be advised to increase power output (Abbiss et al., 2009; Sargeant, Hoinville & Young, 1981).

The effect of cadence on muscular fatigue has been extensively investigated with higher cadences leading to a faster decline in muscular fatigue (Beelen and Sargeant, 1991; Hill, Smith, Leuschel, Chasteen & Miller, 1995; Vanhatalo et al., 2008). Due to the physiological basis of the 3-minute all-out cycling test, it is imperative that the finite work capacity is exhausted within the first 150-seconds of the test. A faster decline in fatigue is, therefore, likely to result in a lower EP, which, in turn may provide a more accurate estimate of CP. McCartney, Heinenhauser and Jones (1985) found that the decline in average power observed during a 30-second maximal effort was less at 60 rev·min^{-1} compared to 140 rev·min^{-1}. Vanhatalo et al. (2008) have suggested that an increase in fatigue at higher cadences could be due to the fatiguing qualities of type I and II muscle fibres. It was suggested that the high cadences observed during the initial stages of the 3-minute all-out test, especially during the high cadence condition, results in sub-optimal cadences for peak power production. Dekerle et al. (2014) also observed reductions in EP when using a higher cadence during the 3-minute all-out test, suggesting that fast twitch muscle fibres are less fatigue resistant. These results highlight the challenges faced when using the participant's preferred cadence to set the fixed resistance during the 3-minute all-out cycling test. The effect of cadence on muscular fatigue may also influence the original CP protocol. Green, Bishop and Jenkins (1995) found that W' is significantly increased if the end-test cadence is reduced from 70 to 60 rev·min^{-1}. To standardise testing sessions, the TTE tests were terminated when the participants' cadence dropped by more than 10 rev·min^{-1} below their preferred cadence. However, they were not instructed to maintain a set cadence throughout each test. Table 2 highlights the differences in mean cadence during each test and, with a difference of ~7 rev·min^{-1} between the 80, 100 and 105% TTE tests, it is reasonable to assume that this could affect the calculations of both CP and W'. It is also possible that the accuracy of the original CP protocol may have been affected by the selection of only three TTE tests. Although three TTE tests have successfully been used to calculated CP and W' (deLucas et al., 2012), some authors have used five or more TTE tests (Poole, Ward, Gardner & Whipp, 1988). In a recent study by Mattioni Maturana et al. (2017), the authors concluded that the mathematical model, number and duration of TTE tests used can affect the calculation of CP and W'. Although their findings support the use of the linear 1/time mathematical model from three TTE tests, CP may vary by approximately 12 W depending on the duration of each test. All participants in the present study reached exhaustion within 2–15 minutes for each TTE test, as stipulated by Jones et al. (2010). However, the results from the Mattioni Maturana et al. (2017) study may suggest that slightly longer TTE tests should be included (e.g. ≤20 minutes) to ensure accurate estimations of CP. Participants also reached a post-test blood lactate above 8 $\text{mmol}\cdot\text{L}^{-1}$ and an end test RER of >1.15 during all TTE tests suggesting that a maximal effort was given during each TTE.

A limitation of the present study is that a CP validation test was not included to ensure that a physiological steady state had been established (Mattioni Maturana, 2016). However, this is a common limitation within the literature and it should also be noted that the original research by Vanhatalo et al. (2007) on the 3-minute all-out cycling test did not include a CP validation test. Based on the concerns above it is reasonable to suggest that the linear 1/time model may not have provided the most accurate method for calculating CP. Without completing a CP validation test, it is not possible to say with certainty that the original or 3-minute all-out cycling test provided a true estimation of CP, and therefore, the demarcation between the heavy and severe exercise intensity domains.

It has been demonstrated how cadence selection can affect the accuracy of CP testing protocols. These results have led some authors to investigate alternative testing protocols (Clark et al. 2013; Dicks et al. 2016). Clark et al. (2013) noted that some participants failed to complete the 3-minute all-out cycling test when the resistance was set according to the protocol described by Vanhatalo et al, (2007). Clark, Murray and Pettitt (2013) investigated the possibility of setting the fixed resistance using a percentage of body mass (%BM) and took into consideration the fitness levels of each participant: 3%BM for recreationally active, 4%BM for anaerobic and aerobic athletes and 5%BM for endurance athletes. Dicks et al. (2016) have also investigated an alternative testing protocol by estimating 50%Δ from a self-reporting of physical activity rating. These authors concluded that alternative testing protocols can be used for the determination of CP and *W′* from a single testing session. These protocols remove the need to carry out a ramp test to calculate GET and $\dot{V}O_{2peak}$, both prerequisites for setting the resistance using the original linear factor equation. However, although they have been found to provide a similar estimation of CP and *W′*, both rely on making calculations based on estimates and for the participants to self-select their current fitness level.

Although the 3-minute all-out cycling test has been demonstrated to provide similar estimations of CP, there remains a concern about its sensitivity to the fixed resistance used as a result of cadence selection. It is recommended that future research investigates the differences in cadences on a wider range of cyclists, from novice to elite with the aim of providing a more definitive method for identifying the participant’s preferred cadence. Alternatively, a field-based all-out cycling test should be investigated to focus on the physiological underpinning of the 3-minute all-out cycling test rather than the testing protocol and ergometer. Finally, it is essential that future research physiologically validates CP to ensure that the results obtained have a practical application.

Conclusion

The key finding of this study suggests that the 3-minute all-out cycling test is sensitive to changes in cadence. Results show that EP was reduced upon the adoption of higher cadences; an increase of 10 rev·min^{-1} above preferred cadence resulted in an EP similar to CP calculated from the original CP protocol. Results also supported previous research to suggest that WEP is not affected by changes in cadence, although it remains significantly lower than W'. Future research should investigate how an athlete's 'preferred' cadence is determined prior to using the 3-minute all-out cycling test to inform training and race strategy. Furthermore, a physiological validation of the calculation of CP should be included in all future research.

Compliance with Ethical Standards

Conflict of interest: The authors declare that they have no conflict of interest.

Ethical approval: All procedures in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent: Informed consent was obtained from all individual participants included in the study.

References

1. Abbiss, C. R., Peiffer, J. J., & Laursen, P. B. (2009). Optimal cadence selection during cycling. *International SportMed Journal*, *10*, 1–15.
2. Barker, T., Poole, D. C., Noble, M. L., & Barstow, T. J. (2006). Human critical power-oxygen uptake relationship at different pedalling frequencies. *Experimental Physiology*, *91*(3), 621–632.

3. Beaver, W. L., Wasserman, K., & Whipp, B. J. (2012). A new method for detecting anaerobic threshold by gas exchange A new method for detecting threshold by gas exchange anaerobic, 2020–2027.
4. Beelen, a, & Sargeant, a J. (1991). Effect of fatigue on maximal power output at different contraction velocities in humans. *Journal of Applied Physiology, 71,* 2332–2337.
5. Bergstrom, H. C., Housh, T. J., Zuniga, J. M., Camic, C. L., Traylor, D. A, Schmidt, R. J., & Johnson, G. O. (2012). A New Single Work Bout Test to Estimate Critical Power and Anaerobic Work Capacity. *Journal of Strength and Conditioning Research*, *26,* 656–663.
6. Bergstrom, H. C., Housh, T. J., Zuniga, J. O. M., Traylor, D. A, Lewis Jr, R. W., Camic, C. L., Schmidt. R. J., Johnson, G. O. (2014). Differences Among Esitmates of Critical Power and Anaerobic Work Capcity Derived From Five Mathmatical Models and the Three-Minute All-Out Test. *Journal of Strength and Conditioning Research*, *28*, 592–600.
7. Burnley, M., Doust, J. H., & Vanhatalo, A. (2006). A 3-min all-out test to determine peak oxygen uptake and the maximal steady state. *Medicine and Science in Sports and Exercise, 38*, 1995–2003.
8. Burnley, M., Vanhatalo, A., & Jones, A. M. (2012). Distinct profiles of neuromuscular fatigue during muscle contractions below and above the critical torque in humans. *Journal of Applied Physiology*, *113*, 215–223.
9. Chidnok, W., Dimenna, F. J., Bailey, S. J., Wilkerson, D. P., Vanhatalo, A., & Jones, A. M. (2013). Effects of Pacing Strategy on Work Done above Critical power during High-Intensity Exercise. *Medicine & Science in Sports & Exercise, 45*, 1377–1385.

10. Clark, I., Murray, S., & Pettitt, R. (2013). Alternative Procedures for the Three-Minute All-Out Exercise Test. *Journal of Strength and Conditioning Research*, *27*, 2104–2112.

11. Cumming, G. (2014). The new statistics: why and how. *Psychological Science, 25*, 7–29.

12. Davis, J. A., Whipp, B. J., Lamarra, N., Huntsman, D. J., Frank, M. H., & Wasserman, K. (1982). Effect of ramp slope on determination of aerobic parameters from the ramp exercise test. *Medicine and Science in Sports and Exercise*, *14*, 339–343.

13. De Pauw, K., Roelands, B., Cheung, S., de Bas, G., Rietjens, G., & Meeusen, R. (2016). Guidelines to classify subject groups in sport-science research. *International Journal of Sports Physiology and Performance*, *11*, 204–213.

14. Dekerle, J., Barstow, T. J., Regan, L., & Carter, H. (2013). The critical power concept in all-out isokinetic exercise. *Journal of Science and Medicine in Sport, 17*, 640–644.

15. de Lucas, R. D., Greco, C. C., Dekerle, J., Carita, R. A. C., Guglielmo, L. G. A., & Denadai, B. S. (2014). Test-retest reliability of a 3-min isokinetic all-out test using two different cadences. *Journal of Science and Medicine in Sport*, *17*, 645–649.

16. Dicks, N. D., Jamnick, N. A., Murray, S. R., & Pettitt, R. W. (2016). Load determination for the 3-minute all-out exercise test for cycle ergometry. *International Journal of Sports Physiology and Performance*, *11*, 197–203.

17. Francis, J. T., Quinn, T. J., Amann, M., & LaRoche, D. P. (2010). Defining intensity domains from the end power of a 3-min all-out cycling test. *Medicine and Science in Sports and Exercise, 42*, 1769–1775.

18. Gaesser, G. A., & Wilson, L. A. (1988). Effects of continuous and interval training on the parameters of the power-endurance time relationship for high intensity exercise. *International Journal of Sports Medicine, 9*, 417–421.

19. Green, S., Bishop, D., & Jenkins, D. (1995). Effect of end-point cadence on the maximal work-time relationship. *European Journal of Applied Physiology and Occupational Physiology, 71*, 559–561.

20. Hill, D., Smith, J., Leuschel, J., Chasteen, S., & Miller, S. (1995). Effect of Pedal Cadence on Parameters of the Hyperbolic Power - Time Relationship. *International Journal of Sports Medicine*, *16,* 82–87.

21. Hill, D. W. (1993). The Critical Power Concept: A Review. *Sports Medicine*, *16,* 237–254.

22. Jenkins, D., & Quigley, B. M. (1990). Blood lactate in trained cyclists during cycle ergometry at critical power. *European Journal of Applied Physiology, 61*, 278–283.

23. Johnson, T. M., Sexton, P. J., Placek, A. M., Murray, S. R., & Pettitt, R. W. (2011). Reliability analysis of the 3-min all-out exercise test for cycle ergometry. *Medicine and Science in Sports and Exercise*, *43,* 2375–2380.

24. Jones, A. M., Vanhatalo, A., Burnley, M., Morton, R. H., & Poole, D. C. (2010). Critical power: implications for determination of VO_{2max} and exercise tolerance. *Medicine and Science in Sports and Exercise*, *42,* 1876–1890.

25. Karsten, B., Jobson, S. A., Hopker, J., Passfield, L., & Beedle, C. (2014). The 3-min Test Does not Provide a Valid Measure of Critical Power Using the SRM Isokinetic Mode. *International Journal of Sports Medicince, 35*, 304–309.

26. Mattioni Maturana, F., Keir, D. A., McLay, K. M., & Murias, J. M. (2016). Can measures of critical power precisely estimate the maximal metabolic steady-

state? *Applied Physiology, Nutrition and Metabolism*, 41, 1197–1203.

27. Mattioni Maturana, F., Fontana F. Y., Pogliaghi, S., Passfield, L., & Murias, J. M. (2017). Critical power: How different protocols and models affect its determination. *Journal of Science and Medicine in Sport* (published online ahead of print 22 November 2017). Available at: https://www.ncbi.nlm.nih.gov/pubmed/29203319 (Accessed 04 March 2018).
28. McCartney, N., Obminski, G., & Heinenhauser, G. (1985). Torque-velocity relationship in isokinetic cycling exercise. *Journal of Applied Physiology, 58*, 1459–1462.
29. Monod, H., & Scherrer, J. (1965). The Work Capacity of a Synergic Muscular Group. *Ergonomics*, *8*, 329–338.
30. Poole, D. C., Burnley, M., Vanhatalo, A., Rossiter, H. B., & Jones, A. M. (2016). Critical Power: An Important Fatigue Threshold in Exercise Physiology. *Medicine & Science in Sports & Exercise*, 48, 2320–2334.
31. Poole, D. C., Ward, S. A, Gardner, G. W., & Whipp, B. J. (1988). Metabolic and respiratory profile of the upper limit for prolonged exercise in man. *Ergonomics*, *31*, 1265–1279.
32. Robergs, R. A., Dwyer, D., & Astorino, T. (2010). Recommendations for improved data processing from expired gas analysis indirect calorimetry. *Sports Medicine*, *40*, 95–111.
33. Sargeant, A. J., Hoinville, E., & Young, A. (1981). Maximum leg force and power output during short-term dynamic exercise. *Journal of Applied Physiology, 51*, 1175–1182.
34. Smith, J. C, Hill, D. W. (1993). Stability of parameter estimates derived from the power/time relationship. *Journal of Applied Physiology, 18*, 43–47 .

35. Vanhatalo, A., Doust, J. H., & Burnley, M. (2007). Determination of critical power using a 3-min all-out cycling test. *Medicine and Science in Sports and Exercise*, *39*, 548–555.

36. Vanhatalo, A., Doust, J. H., & Burnley, M. (2008). Robustness of a 3 min all-out cycling test to manipulations of power profile and cadence in humans. *Experimental Physiology*, *93*, 383–390.

37. Waldron, M., Gray, A., Furlan, N., & Murphy, A. (2016). Predicting the Sprint Performance of Adolescent Track Cyclists Using the 3-Minute All-out Test. *Journal of Strength and Conditioning Research*, *30*, 2299–2306.

38. Whipp, B. J. (1996). Domains of aerobic function and their limiting parameters. In: Steinacker, J. M., & Ward, S. A. (Eds.), *The Physiology and Pathophysiology of Exercise Tolerance* (pp. 83–89). Plenum, New York.

39. Wright, J., Bruce-Low, S., & Jobson, S. A. (2017). The Reliability and Validity of the 3-min All-out Cycling Critical Power Test. *International Journal of Sports Medicine*, *38*, 462–467.

Table 1. Mean values (± SD) observed during each 3-minute all-out cycling test.

	Preferred Cadence	Preferred Cadence -5 rev·min^{-1}	Preferred Cadence $+5$ rev·min^{-1}	Preferred Cadence $+10$ rev·min^{-1}
$\dot{V}O_{2peak}$ (L·min^{-1})	4.8 ± 0.4	4.7 ± 0.6	4.8 ± 0.5	4.7 ± 0.6
Peak power (W)	872.7 ± 181.9	932.0 ± 190.3	798.4 ± 157.1	784.4 ± 140.9
EP (W)	297.4 ± 25.8	303.6 ± 24.0	290.0 ± 28.0	278.1 ± 30.9*
Peak cadence (rev·min^{-1})	157.0 ± 14.6	155.8 ± 13.0	159.3 ± 13.8	164.7 ± 11.8
End cadence (rev·min^{-1})	93.0 ± 4.0	90.1 ± 2.2	98.3 ± 2.8*	101.6 ± 3.4*
WEP (kJ)	11.2 ± 4.5	12.6 ± 4.0	11.0 ± 4.4	10.9 ± 4.8

*Significantly different from Preferred Cadence ($P < 0.05$)

Table 2. Standard error of estimates and Pearson's product moment correlation coefficients between CP with EP and between *W′* with WEP calculated at each cadence.

	R	SEE
CP vs. EP-preferred	0.91, $P < 0.001$	9.92 W
CP vs. EP−5	0.87, $P < 0.000$	11.85 W
CP vs. EP+5	0.91, $P < 0.000$	9.81 W
CP vs. EP+10	0.92, $P < 0.000$	9.37 W
W′ vs. WEP-preferred	0.68, $P = 0.030$	3.92 kJ
W′ vs. WEP−5	0.50, $P = 0.140$	4.64 kJ
W′ vs. WEP+5	0.47, $P = 0.173$	4.74 kJ
W′ vs. WEP+10	0.42, $P = 0.229$	4.88 kJ

Table 3. Mean (± SD) cadence, peak oxygen uptake and time to exhaustion observed during each testing session.

Testing session	Cadence (rev·min^{-1})	$\dot{V}O_{2peak}$ (L·min^{-1})	Time to exhaustion (s)
$\dot{V}O_{2peak}$ ramp test	93.3 ± 4.1	4.8 ± 0.4	675 ± 87
80% MAP	89.5 ± 4.6	4.6 ± 0.4	714 ± 143
100% MAP	94.3 ± 2.5	4.5 ± 0.6	203 ± 40
105% MAP	96.2 ± 3.4	4.6 ± 0.5	166 ± 31

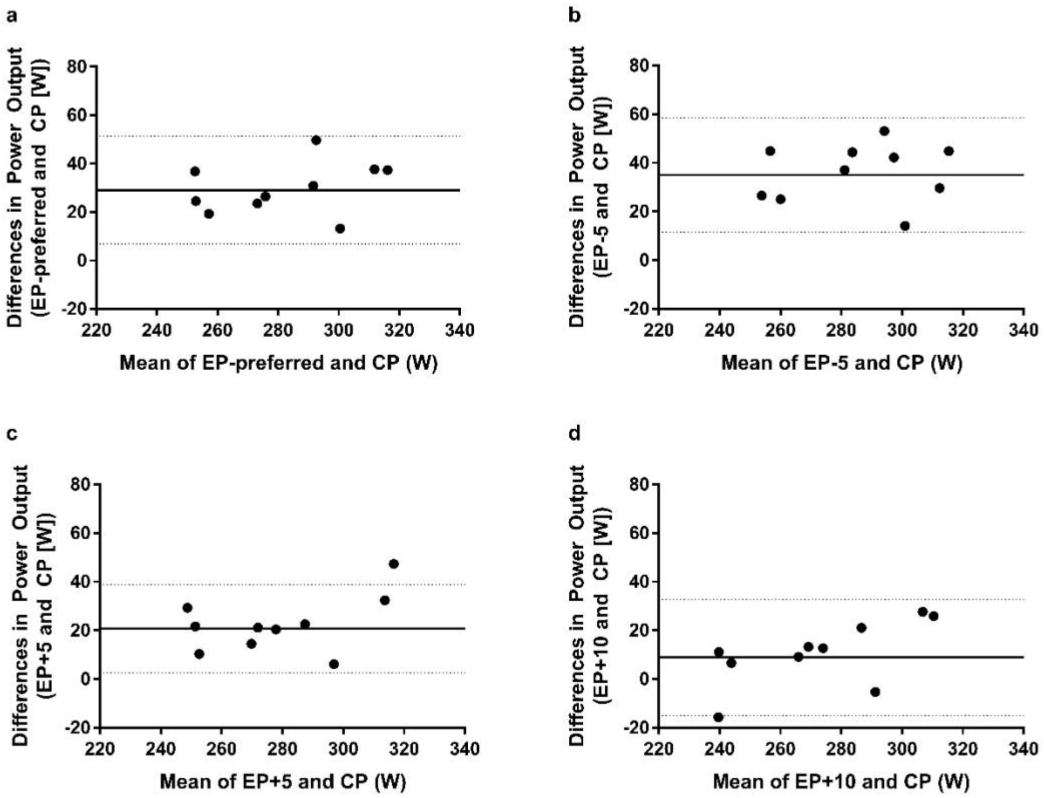

Figure 1. Bland-Altman plots showing the limits of agreement between CP and EP-preferred (a), CP and EP−5 (b), CP and EP+5 (c) and CP and EP+10 (d). The solid line represents the mean difference in power output and the dashed line represents the 95% limits of agreement.

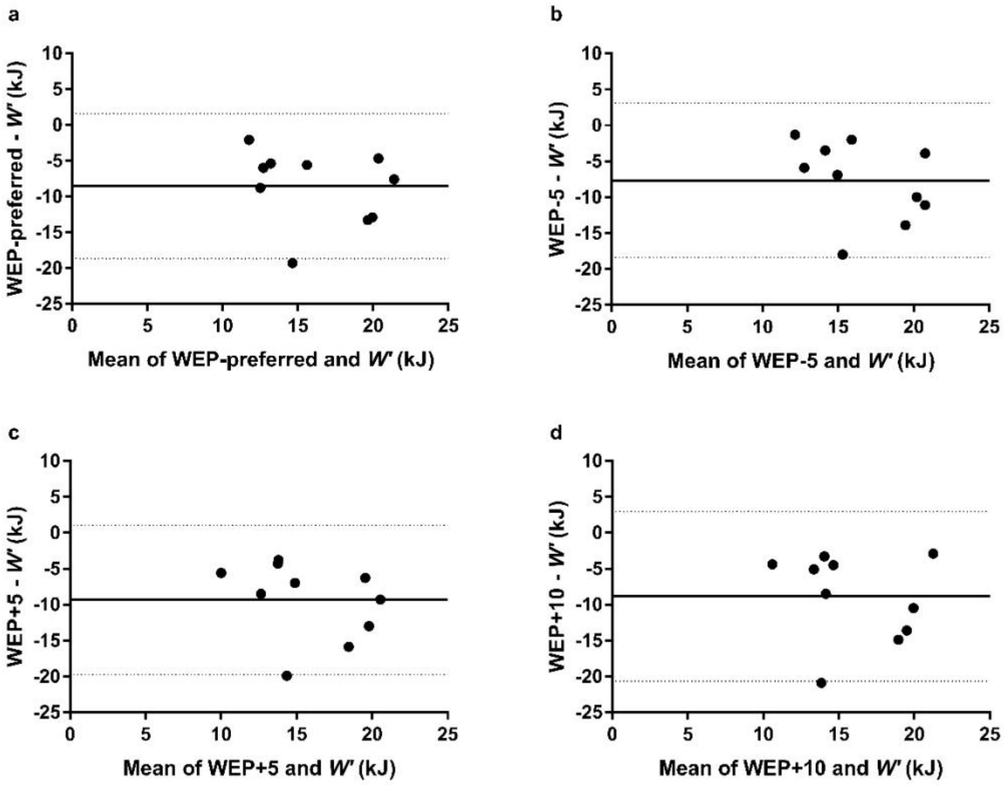

Figure 2. Bland-Altman plots showing the limits of agreement between *W′* and WEP-preferred (a), *W′* and WEP−5 (b), *W′* and WEP+5 (c) and *W′* and WEP+10 (d). The solid line represents the mean difference in power output and the dashed line represents the 95% limits of agreement.

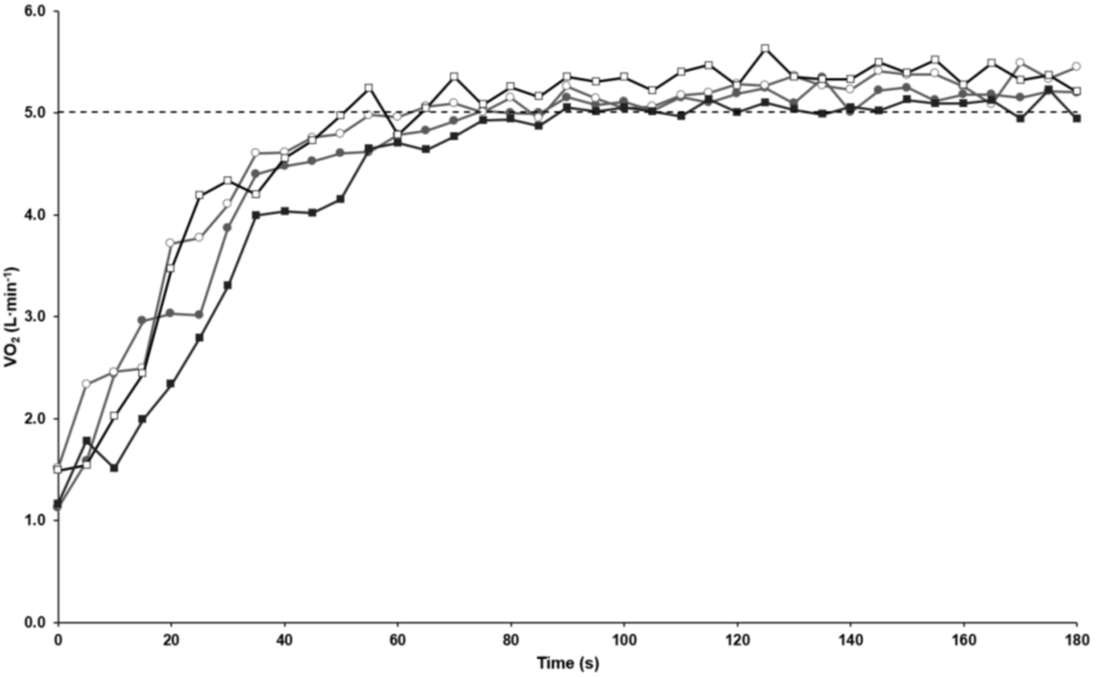

Figure 3. Example $\dot{V}O_2$ uptake observed during the 3-minute all-out cycling test. Note that $\dot{V}O_{2peak}$ is attained within the first 90 seconds and then maintained for the duration of the test. Preferred cadence = closed circles, preferred cadence –5 rev·min^{-1} = open circles, preferred cadence +5 rev·min^{-1} = closed squares and preferred cadence +10 rev·min^{-1} = open squares. The dashed line represents 95% $\dot{V}O_{2peak}$ calculated from the initial ramp protocol.