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High agreement between laboratory and field estimates of critical power in cycling

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ABSTRACT

The purpose of this study was to investigate the level of agreement between field-based and laboratory-based estimates of critical power (CP) in cycling. Subjects were fourteen trained cyclists (age 40 ± 7 yrs; body mass 70.2 ± 6.5 kg; $\dot{V}O_{2\,max}$ 3.8 ± 0.48 L·min^{-1}). Laboratory-based CP was estimated from three constant work-rate tests performed on a cycle ergometer at 80%, 100% and 105% of maximal aerobic power (MAP). Field-based CP was estimated from three all-out tests performed on an outdoor velodrome over fixed durations of 3, 7 and 12 minutes. Using the linear work limit (W_{lim}) versus time limit (T_{lim}) relation and the inverse time (1/t) versus power (P) models, field-based CP1 and CP2 values did not significantly differ from laboratory-based values (234 ± 24.4W vs. 234 ± 25.5W (CP1); $P < 0.001$, $r^2 = 0.95$; limits of agreement [LOA], −10.98 to 10.8 W and 236 ± 29.1W vs. 235 ± 24.1W (CP2); $P < 0.001$, r2 = 0.95 [LOA], -13.88 to 17.3 W. Data suggest that employing all-out field tests lasting 3, 7 and 12 minutes has potential utility in the estimation of CP.

Key Words: critical intensity, exercise testing, power-duration relationship

Introduction

Performance tests are a key component in the training of athletes, providing markers of performance that can be used as an indicator of training status. One such marker is critical power (CP).
In the hyperbolic relationship between power output and time to fatigue, CP represents the highest prolonged sustainable work rate, whilst the curvature constant (*W'*) relates to a finite amount of energy which can be performed above CP [11, 12, 29]. Poole et al. [30] characterized the physiological response to exercise performed at CP, showing that CP represents the highest power output at which $\dot{V}O_2$ and blood lactate stabilize. Theoretically CP is sensitive to changes in performance capacity which are likely to occur frequently during athletic training, and therefore provides a useful indicator of training status.

In cycling CP is traditionally estimated in laboratory conditions by using time to exhaustion (TTE) trials at fixed intensities [6, 22, 30]. An estimation of maximal aerobic power (MAP) is required to calculate the intensity in question. The total number of trials required to estimate CP ranges between 3 and 5 [5, 13, 20, 21, 30, 37], although it is usual for at least 3 trials to be performed, especially in non-elite athletes. Given this, laboratory estimation of CP can be time consuming and potentially disruptive to an athlete's training programme.

The estimation of CP in cycling has traditionally been lab-based, other sports have used field-based estimates of the related phenomenon of Critical Velocity (CV). Wakayoshi [42] and Dekerle [7] suggested that the field estimation of CV in swimmers requires only two performances (200m and 400m). In running Kranenburg and Smith [24] estimated lab CV using constant load tests on a treadmill that induced exhaustion within 3, 7 and 12 mins, and employed three set distances, each run on an indoor track, to estimate field CV. The authors reported that this field-based method of estimating CV proved robust, and that field CV was significantly related to 10 km race speed. Again in running, Galbraith et al. [14] developed a field test to determine critical speed also using set

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distances yielding finishing times between 2 and 12 minutes. Both studies used three trials of durations between 3 and 12 min, and used trained subjects. Hiyanne et al. [18] estimated CV using all-out cycling tests over distances of 2, 4 and 6 km resulting in testing times between 1 and 10 minutes.

Whilst conditions in the laboratory are more controllable, arguably providing greater reliability, field tests have the advantage of providing greater ecological validity [19, 26]. Such validity might be a function of many factors. For example, field tests allow the athlete to perform in an environment consistent with that in which they usually compete, permitting previously acquired effort regulation skills to be employed, therefore reducing the need for habituation to laboratory protocols. Field tests are also relatively unconstrained by the mechanical limitations often imposed by laboratory equipment. Contrast for example cycling on a velodrome with riding a mechanically stable ergometer; in the former the bike moves laterally under the rider, and the rider is likely to have developed a handling technique that both controls for this and in doing so optimises the contribution to forward motion of various synergistic and stabilising components of the skeletal- and neuro-muscular systems. These components are less likely to be employed in all but the most ecologically valid laboratory settings. These factors are especially pertinent if the performance in question is measured over a pre-set time, as opposed to time to exhaustion[1]. The former better replicate the characteristics of most sports events, which take place over fixed distances or times and which rarely entail performance to the point of volitional exhaustion. It goes without saying that a further benefit of field testing is that it widens access to the techniques and knowledge base of traditionally laboratory-based sports sciences, especially to athletes and coaches with low financial resources.

[1] Whilst TTE protocols have frequently been used in sports research [8, 43], they are often associated with low reliability. For example, using untrained subjects Krebs and Power [25] and McLellean et al. [27] reported coefficient of variation (CoV) values ranging between 5.2–56.0% and 2.8–31.0% respectively. Even using well-trained cyclists, Jeukendrup et al. [23] reported CoV values ranging between 17 and 40%. In contrast with TTE protocols, testing protocols that employ a fixed quantity of work, distance or time are reported to be more reliable [2, 17, 23, 28, 33, 34]. However, we recognise that in conducting the present study we have based our field estimates of CP on laboratory estimates derived through TTE protocols.

Whilst all of the above advantages hold true for many settings, the major limitation with field testing is the lack of control over environmental variables. Even in relatively controlled environments such as indoor athletics tracks, velodromes and swimming pools, variations in temperature and humidity, and disturbances in air or water flow caused by other athletes, can reduce reliability of measurement. This of course becomes a far more serious problem in outdoor road or track cycling where wind and temperature conditions can vary substantially within minutes. In modelling cycling performance in varying wind conditions, Swain [38] used a circuit course which contained equal-length segments of headwind and tailwind. The modelled time for trials was greater in wind conditions compared to no-wind conditions, these greater times resulting from the slowdown of the cyclist into headwinds, which were greater than time saved with tailwinds. Counter to this suggestion Quod et al. [32] compared values of CP and power observed in the laboratory with those observed in competition, and reported no significant differences between the two ($p = 0.09$, relative difference -0.8%).

To date, only two studies have employed field settings for the estimation of CV [18] and CP [32] in cycling. The purpose of the present study was to use a method similar to that of Kranenburg and Smith [24] to compare values of CP derived through laboratory-based TTE trials with values of CP derived through field tests using trials of set durations.

Methods

Subjects

Twelve male and two female cyclists were recruited from local cycling clubs (males: mean ± SD: age 40 ± 6 yrs; body mass 72.1 ± 4.8 kg; $\dot{V}O_{2\,max}$ 3.9 ± 0.4 L·min^{-1}; MAP 320.6 ± 23.4 W; females: mean ± SD: age 38 ± 11 yrs; body mass 57.8 ± 0.28 kg; $\dot{V}O_{2\,max}$ 3.2 ± 0.21 L·min^{-1}; MAP 256.0 ± 2.4 W). All subjects had been involved in regular cycling training and competition for a minimum 2 years. The study was performed in accordance with the ethical standards of the International Journal of Sports Medicine [16] and approved by the University Ethics Committee. Prior to providing written informed consent and participation, cyclists were fully informed of the nature and risks of the study.

Protocol

The study used a within-subject design. During the first laboratory session maximal oxygen consumption ($\dot{V}O_{2\,max}$) and MAP values were established. Subjects then performed three laboratory-based ergometer CP tests and three field CP tests all randomised (below). Subjects were not informed of their performance outcomes until the completion of the study. To minimise training effects each subject completed all seven sessions 21 days. A minimum of 24 hours rest was required between individual tests [6, 31].

A road bicycle equipped with a PowerTap Elite wheel (CycleOps, Madison, USA) was used to measure work in both laboratory and field tests [15]. The saddle and handlebar were adjusted to suit each participant and settings were replicated exactly during subsequent tests. For laboratory testing the bicycle was attached to a Computrainer (RacerMate, Seattle, USA). Prior to each test the Powertap was zero adjusted according to the manufacturer's instructions.

Maximal oxygen uptake test protocol

Following a standardised warm-up (5 min cycling at 100W, followed by 3 min unloaded phase), subjects completed a progressive, incremental laboratory exercise test to exhaustion. Expired gases were collected continuously throughout the test using a MetaMax gas analyser (MetaMax 3B, Cortex Biophysik, Leipzig, Germany). Blood lactate was analysed using the Biosen C_line analyser (EFK Diagnostics, Barleben, Germany) and heart rate was continuously monitored using the PowerTap. The maximal test commenced at a work rate of 150 W for male and 120 W for female cyclists (females have lower absolute peak power values than males [39] and a max test should last somewhat between 8 and 10 minutes for moderately to trained subjects [44]. Thereafter, intensity increased at a step rate of 20 $W \cdot min^{-1}$ using P values obtained from the PowerTap. Consistent with previous CP research [41] cyclists' preferred cadence was used throughout the test. The test was terminated when cadence dropped by more than 10 $rev \cdot min^{-1}$ for more than 10 seconds. MAP was calculated as the highest

mean P values (W) over the final 60 seconds. $\dot{V}O_{2\,max}$ was calculated as the highest mean oxygen consumption over a 30-second period.

Laboratory based Critical Power tests

Cyclists completed three tests to exhaustion on the equipment described above. All tests were performed on separate days at work rates equivalent to 80%, 100% and 105% of MAP. After a 5-min warm-up at a work rate of 100 W, the test resistance was set and cyclists were instructed to maintain their preferred cadence for as long as possible. Heart rate (HR), P and cadence were logged continuously by the PowerTap. Consistent with previous CP research [41] strong verbal encouragement was provided throughout the tests. Tests were terminated when cadence dropped by 10 rev·min^{-1} below preferred cadence for more than 10 seconds. Capillary blood samples were collected at rest, immediately post-test and 3 min post test and analysed for lactate concentration. Consistent with published guidelines [3] a post-test blood lactate concentration of ≥ 8 mmol·l^{-1} or HR within 10 beats of age-predicted HR maximum was taken as an indicator for attainment of $\dot{V}O_{2\,max}$ and accepted as a successful test.

Field based Critical Power tests

Subjects were tested over fixed times of 3, 7 and 12 min rather than over set distances [29] on an outdoor velodrome. Tests were completed on separate days and in randomised order. Tests started from a standing position, and subjects were instructed to ride around the velodrome as fast as possible in each test. Feedback regarding remaining time, as well as verbal encouragement, was provided throughout the tests. Capillary blood samples were taken at rest, immediately post-test and 3 min post test. A post-test blood [lactate] of ≥ 8mmol·l^{-1} or HR within 10 beats of age-predicted HR maximum was taken as an indicator for attainment of $\dot{V}O_{2\,max}$ and accepted as a successful all-out test [3].

Control of environmental factors

As suggested above, environmental conditions are a major concern in field testing. Consistent with the data reported by Swain [38], it was initially decided that field testing would not take place in wind speeds above 6.6 $m \cdot s^{-1}$, or in rain or otherwise wet conditions. The latter scenario was relatively straight forward to address. However, wind speed so frequently exceeded the 6.6 $m \cdot s^{-1}$ level that cancelling tests on the basis of this criterion would have extended data collection beyond the 21-day criterion and might have introduced other sources of error (e.g., training/de-training effects). As seriously, cancelling on the basis of wind speed – which would have led to several tests being abandoned once underway – would likely have led to subjects dropping out of the study. Therefore testing went ahead irrespective of measured wind speed, and this issue and decision is discussed further below.

Calculation of Critical Power and *W′*

Linear regression was used to provide an estimate of CP and *W′* from the results of the laboratory and the field trials using the work-time model [$P = W' + (CP \cdot t)$] are consequently termed CP1 and *W′*1 and using the power-1/time model [$P = (W' / t) + CP$] are consequently termed CP2 and *W′*2.

Statistical Methods

The distribution of each variable was examined with the Shapiro-Wilks' normality test. Pearson product moment correlation analysis was used to provide an indication of the strength of any relationship between field- and laboratory-derived CP1 and CP2 and *W′*1 and *W′*2. Agreement between laboratory and field CP1 and CP2 and *W′*1 and *W′*2 was assessed using a paired samples *t*-test and Limits of Agreement (LOA; [1, 4]). Paired samples *t*-tests were conducted to identify any differences in laboratory and field based CP TTE trials, in maximal lactate concentration, and maximal HR for each equivalent test (80% and 12 min, 100% and 7 min, 105% and 3 min) and for differences between relative percentage of MAP achieved during the laboratory- and field-based CP1 and CP2 tests. Statistical significance was accepted at $P < 0.05$. Results are reported as mean ± SD unless otherwise stated.

Results

No significant difference were observed between field-based and laboratory-based CP1 (234 ± 24.4W vs. 234 ± 25.5W respectively; t (13) = 0.97, p = 0.924) and CP2 (234 ± 24.4W vs. 234 ± 25.5W respectively; t (13) = 0.81, p = 0.435). Data recorded in the two environments were highly correlated (r = 0.976; p < .05 (CP1) and r = 0.973; p < .05 (CP2). Mean difference between laboratory- and field-based values for CP1 was 0.17 +/- 5.72 W (95% CI, - 3.14-16.61; limits of agreement [LOA], −10.98 to 10.8 W) and for CP2 it was 2 +/- 7.72 W (95% CI, -2.28 -25.35; [LOA], -13.88 to 17.3 W). Significant differences were observed between laboratory- and field-based *W′*1 (12.2 ± 2.7kJ vs 17.3 ± 5.4kJ respectively, t (13) = -3.98, p = 0.02) and *W′*2 (11.6 ± 2.7kJ vs. 16.5 ± 4.8kJ respectively; t (13) = -3.93, p = 0.02). The mean difference in *W′*1 was -5.1 +/- 4.8kJ (95% CI, -7.86 – 9.14; [LOA], -14.5 to 4.3 kJ) and in *W′*2 it was -4.9+/- 4.7kJ (95% CI, -7.58 – 8.94; [LOA], -14.0 to 4.2 kJ). Analysis of [blood] lactate ($mmol \cdot l^{-1}$) revealed significantly higher concentrations for field-based testing when comparing the 100% TTE trial versus the 7 min test (t (13) = -2.12, p = 0.035) and the 105% TTE trial versus the 3 min test (t (13) = -2.36, p = 0.009) whilst the 80% TTE trial versus the 12 min test did not result in a statistically significant but low p-value (0.054) (see Table 1).

---Figure 1 about here---

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Ferguson et al. [9, 10] in their CP research added another TTE trial if individual SE values for a CP estimate fell above or below that of 3 W. Interestingly individual SE values of ± 3 W in the present study fit well for the linear work-time model of laboratory and field-based CP estimates but lie above (~ 8 W) of the recommended value in the power-1/time-power model.

Discussion

A mean difference between laboratory- and field-derived estimates of CP of 0.2 ± 5.7 W, suggests that field testing might provide a valid estimate of CP in cycling. Results support those of Quod et al [32], Kranenburg and Smith [24], and Galbraith et al. [14].

Whilst in designing the study, the research team were optimistic that the field-based estimation of CP held some promise, differences between laboratory-based and field-based values of CP were lower than anticipated, especially given that the velodrome used for field testing provided no shelter and wind speeds above the 6 $m \cdot s^{-1}$ criterion suggested by Swain [38] were frequently observed. Given the linear function between work completed and time, any deviation of this linearity due to unequal headwind and tailwind speeds would have been identified in the individual CP1/CP2 field-based plots (the mean r-value for field-based CP1 was 0.99 ± 0.001 and for field-based CP2 it was 0.99 ± 0.008). Therefore our data do not appear to support those of Swain, and individual SE values reported above appear to support this position. Of course, given the relatively small number of subjects there is the possibility that the findings are due to chance. They will need to be tested on different, and ideally larger, samples.

Another aspect of the data worthy of discussion are the significant differences between laboratory and field-based estimates of *W'*1 and *W'*2. Field-based estimates for *W'*1 were on average 5.09 kJ and for *W'*2 4.89 kJ higher than the respective laboratory values. This is accompanied by overall higher blood [lactate] responses for field testing (Table 1) and by a difference in power profiles between laboratory and field. Table 2 illustrates the initial 10 and 30 seconds of the all tests. Testing in the field began from a standing start with an initial acceleration phase whilst constant load testing was performed at a constant cadence with the resistance increasing to the required intensity at the beginning of each TTE trial. This difference in power profile is most pronounced in the shorter field trials (3 and 7 min). During the acceleration phase in the field subjects likely utilized a higher portion of type II muscle mass resulting in significantly higher power and blood [lactate] values [35, 40] compared to the constant load tests. The relative rate of field-based *W'* (kJ) expenditure therefore also seems to be

greater when compared to the laboratory testing. Skiba *et al.* [36] suggested that *W′* may be primarily a representative of exercising type I and type II muscle mass but that the sum of *W′* expended at exhaustion is equal to the known total *W′*. If this is true than the difference between laboratory- and field-based *W′* estimates might be explained by the difference in environmental or testing conditions (i.e. standing start, acceleration against air resistance or use of body weight during the acceleration phase) and further work is required to shed some light into the different *W'* estimates.

In summary, it is recognised that the estimation of CP provides a useful indicator of training status. CP has traditionally been estimated in the laboratory. Results of the present study whilst suggesting a significant difference in *W′* between the laboratory and the field, also suggest a high agreement in CP between the same environments. The field estimation of CP may offer a more ecologically valid and less expensive alternative to traditional approaches, making it a more widely available test. Interestingly, in line with the findings of Kranenburg and Smith [24], subjects in the present study indicated a preference for field testing since it provided a more sports specific test in terms of both movement mechanical and pacing. We do however caution that above findings, promising though they are, require replication.

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Legends

Fig. 1. Illustration of the correlation between CP1 and CP2 values derived from laboratory and field tests (C and D) and the residuals between laboratory and field based CP using the Bland Altman test for the relation and bias (solid line) ± 95% limits of agreement (dashed lines) between laboratory-based CP1/2 and field-based CP1/2 (A and B).

Fig. 2. Illustration of the correlation between $W'1$ and $W'2$ values derived from laboratory and field tests (C and D) and the residuals between laboratory and field based W' using the Bland Altman test for the relation and bias (solid line) ± 95% limits of agreement (dashed lines) between laboratory-based $W'1/2$ and field-based $W'1/2$ (A and B).

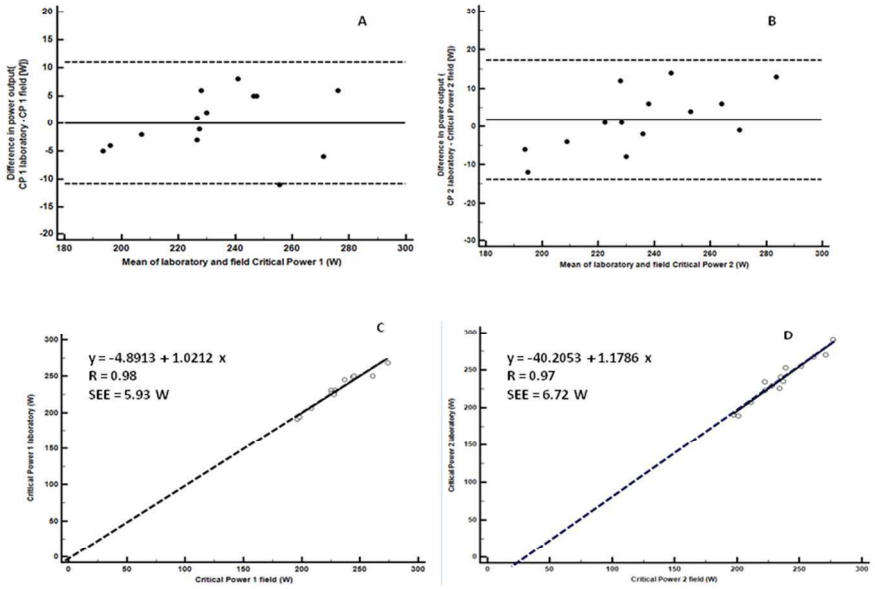

Figure 1 - Illustration of the correlation between CP1 and CP2 values derived from laboratory and field tests (C and D) and the residuals between laboratory and field based CP using the Bland Altman test for the relation and bias (solid line) ± 95% limits of agreement (dashed lines) between laboratory-based CP1/2 and field-based CP1/2 (A and B).

German:
Figur 1. Illustration der Uebereinstimmung der CP1 und CP2 Werten, ermittelten Feldtests (C und D) und den individuellen Differenzen zwischen CP Labor und Feldtest Werten unter Benutzung des Bland Altman Tests fuer Beziehung und Ueberschnitt (durchgezogenen Linie) ± 95% Uebereinstimmungsgrenze (gestrichelte Linie) zwischen Labortest CP1/2 und Feldtest ermittelten CP1/2 Werten (A und B)
254x190mm (96 x 96 DPI)

Table 1. Group maximal [blood] lactate ($mmol \cdot l^{-1}$) results, p-values and confidence intervals of the difference for each test

	105% MAP	3 min	p-value	Lower- upper 95% confidence intervals of the difference	
Lactate ($mmol \cdot l^{-1}$)	12.26 (±2.29)	14.22 (±2.98)	0.009[a]	-3.34	-0.58
	100% MAP	7 min	p-value	Lower - upper 95% confidence intervals of the difference	
Lactate ($mmol \cdot l^{-1}$)	13.55 (±1.99)	15.19 (±2.75)	0.035[b]	-3.14	-0.14
	80% MAP	12 min	p-value	Lower- upper 95% confidence intervals of the difference	
Lactate ($mmol \cdot l^{-1}$)	13.84 (± 3.30)	14.95 (± 3.09)	0.054	-2.25	-0.021

Values are mean (± SD).

[a] = significantly different from the mean 105% constant work load lactate values ($P < 0.05$).

[b] = significantly different from the mean 100% constant work load test ($P < 0.05$).

Table 2. Mean initial 10 s and 30 s P values (W) for field and laboratory-based tests

Field Test	Initial 10 s P (W)	Laboratory Test	Initial 10 s P (W)
Test 1	12 min = 532 ± 184 W	Test 1	80% TTE = 179 ± 38 W
Test 2	7 min = 624 ± 133 W	Test 2	100% TTE = 174 ± 38 W
Test 3	3 min = 633 ± 148 W	Test 3	105% TTE = 204 ± 34 W
Field Test	Initial 30 s P (W)	Laboratory Test	Initial 30 s P (W)
Test 1	12 min = 451 ± 132 W	Test 1	80% TTE = 212 ± 45 W
Test 2	7 min = 496 ± 108 W	Test 2	100% TTE = 230 ± 40 W
Test 3	3 min = 524 ± 95 W	Test 3	105% TTE = 279 ± 45 W