# High Agreement between Laboratory and Field Estimates of Critical Power in Cycling

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## Abstract
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The purpose of this study was to investigate the level of agreement between laboratory-based estimates of critical power (CP) and results taken from a novel field test. Subjects were fourteen trained cyclists (age $40 \pm 7$ yrs; body mass $70.2 \pm 6.5$ kg; $\dot{V}O_{2max}$ $3.8 \pm 0.5$ L·min$^{-1}$). Laboratory-based CP was estimated from 3 constant work-rate tests at 80%, 100% and 105% of maximal aerobic power (MAP). Field-based CP was estimated from 3 all-out tests performed on an outdoor velodrome over fixed durations of 3, 7 and 12 min. Using the linear work limit ($W_{lim}$) vs. time limit ($T_{lim}$) relation for the estimation of CP1 values and the inverse time ($1/t$) vs. power (P) models for the estimation of CP2 values, field-based CP1 and CP2 values did not significantly differ from laboratory-based values ($234 \pm 24.4$ W vs. $234 \pm 25.5$ W (CP1); $P < 0.001$; limits of agreement [LOA], $-10.98–10.8$ W and $236 \pm 29.1$ W vs. $235 \pm 24.1$ W (CP2); $P < 0.001$; [LOA], $-13.88–17.3$ W. Mean prediction errors for laboratory and field estimates were 2.2% (CP) and 27% ($W'$). Data suggest that employing all-out field tests lasting 3, 7 and 12 min has potential utility in the estimation of CP.

## Introduction
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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, while the curvature constant ($W'$) relates to a finite amount of energy which can be performed above CP [13, 14, 32]. Poole et al. [34] 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 [8, 25, 35]. 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 [7, 15, 23, 24, 35, 42], 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.

While 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). In swimming, Wakayoshi [47] and Dekerle [9] suggested that the field estimation of CV in swimmers requires only 2 performances (200 m and 400 m). In running Kranenburg and Smith [28] estimated lab CV using constant load tests on a treadmill that induced exhaustion within 3, 7 and 12 mins, and employed 3 set distances, each run on an indoor track, to estimate field CV. The authors reported that this field-based method of estimating CV proved to be robust, and that field CV was significantly related to 10 km race speed. Again in running, Galbraith et al. [16] developed a field test to determine critical speed also using set distances yielding finishing times between 2 and 12 min. Both studies used three trials of durations between 3 and 12 min, and used trained subjects. Hiyanne et al. [20] estimated CV using all-out cycling tests over distances of 2, 4 and 6 km resulting in testing times between 1 and 10 min.

Data suggest that laboratory and field tests might produce different findings. For example, Jobson et al. [27] reported higher power output values in the field than in the laboratory at given $\dot{V}O_2$ values, while Bertucci et al. [3] found an increased gross efficiency and cycling economy in the field when compared to the laboratory. While conditions in the laboratory are more controllable, providing greater reliability, field tests have the advantage of providing greater ecological validity [21,30]. 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. 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.

While 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 [43] 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 resulted from the slowdown of the cyclist into headwinds, which were greater than time saved with tailwinds. Counter to this suggestion, Quod et al. [37] compared values of CP observed in the laboratory with those observed in competition and reported no significant differences between the 2 (p=0.09, relative difference −0.8%).

To date, only 2 studies have employed field settings for the estimation of CV [20] and CP [37] in cycling. The purpose of the present study was to use a method similar to that of Kranenburg and Smith [28] 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
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### Subjects
12 male and 2 female cyclists were recruited from local cycling clubs (mean±SD: age 40±6yrs; body mass 70.2±6.5kg; $\dot{V}O_{2max}$ 3.8±0.5L·min$^{-1}$; MAP 311±32.5W). 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 [18] 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 an intra-subject design. During the first laboratory session maximal oxygen consumption ($\dot{V}O_{2max}$) and MAP values were established. Subjects then performed 3 laboratory-based ergometer CP tests and 3 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 7 sessions within 21 days. A minimum of 24h rest was required between individual tests [8,36].

A 24 speed road bike (Raleigh Airlite, UK), equipped with a PowerTap Elite wheel (CycleOps, Madison, USA) and a magnet for direct cadence measurement was used to measure work in both laboratory and field tests [17]. 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). To ensure the most accurate power reading the PowerTap was zero-offset prior to each test according to the manufacturer's instructions. According to Bertucci et al. [2] the PowerTap provides a power output accuracy of 1.2±1.3% and coefficient of variation values of 0.9–2.9%. The authors deemed it a valid and reliable measure of power output at submaximal intensities. The same road bike and PowerTap Elite wheel was used for all subjects and tests.

### Maximal oxygen uptake test protocol
Following a standardised warm-up (5min cycling at 100W, followed by 3min 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 150W for male and 120W for female cyclists (females have lower absolute peak power values than males [44] and a maximal test should last somewhere between 8 and 10min for moderately trained to trained subjects [48]). Thereafter, intensity increased at a step rate of 20W·min$^{-1}$ using power values obtained from the PowerTap. Consistent

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[1] While TTE protocols have frequently been used in sports research [10,48], they are often associated with low reliability. For example, using untrained subjects Krebs and Power [29] and McLellean et al. [31] 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. [26] 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 [4,19,26,32,38,39]. However, we recognise that in conducting the present study we have based our field estimates of CP on laboratory estimates derived through TTE protocols.

with previous CP research [46] cyclists' preferred cadence was used throughout the test. The test was terminated when cadence dropped by more than $10\,\text{rev}\cdot\text{min}^{-1}$ for more than 10 s. MAP was calculated as the highest mean power values (W) over the final 60 s. $\dot{V}O_{2max}$ was calculated as the highest mean oxygen consumption over a 30-s period.

### Laboratory-based critical power tests

Cyclists completed 3 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 [46] strong verbal encouragement was provided throughout the tests. Tests were terminated when cadence dropped by $10\,\text{rev}\cdot\text{min}^{-1}$ below preferred cadence for more than 10 s. Capillary fingertip blood samples were collected at rest, immediately post-test and 3 min post-test and analysed for lactate concentration. Consistent with published guidelines [4] a post-test blood lactate concentration of $\geq 8\,\text{mmol}\cdot\text{l}^{-1}$ or HR within 10 beats of age-predicted HR maximum was taken as an indicator for attainment of $\dot{V}O_{2max}$ 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 [34] 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 fingertip blood samples were taken at rest, immediately post-test and 3 min post-test. A post-test blood [lactate] of $\geq 8\,\text{mmol}\cdot\text{l}^{-1}$ or HR within 10 beats of age-predicted HR maximum was taken as an indicator for attainment of $\dot{V}O_{2max}$ and accepted as a successful all-out test [5].

### Control of environmental factors

As suggested above, environmental conditions are a major concern in field testing. Consistent with the data reported by Swain [43], it was initially decided that field testing would not take place in wind speeds above $6.6\,\text{m}\cdot\text{s}^{-1}$, or in rain or otherwise wet conditions. The latter scenario was relatively straight-forward to address. However, wind speed so frequently exceeded the $6.6\,\text{m}\cdot\text{s}^{-1}$ 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). 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 are 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; [1,6]). 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 percentages of MAP achieved during the laboratory- and field-based CP1 and CP2 tests. Additionally, linear regression was used to estimate error associated with predicting field CP and $W'$ values [22]. Statistical significance was accepted at $P < 0.05$. Results are reported as mean ± SD unless otherwise stated.
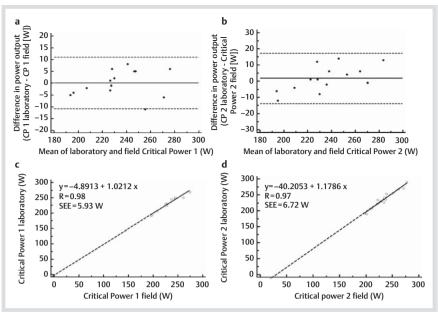
### Results
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No significant differences were observed between field-based and laboratory-based CP1 (234 ± 24.4 W vs. 234 ± 25.5 W respectively; t(13) = 0.97, p = 0.924) and CP2 (235 ± 24.1 W vs. 236 ± 29.1 W respectively; t(13) = 0.81, P = 0.435). Data recorded in the 2 environments were highly correlated (r = 0.976; P < 0.05 (CP1) and r = 0.973; P < 0.05 (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], −10.98–10.8 W) and for CP2 it was 2 ± 7.72 W (95% CI, −2.28–25.35; [LOA], −13.88–17.3 W) (○ **Fig. 1**). Significant differences were observed between laboratory- and field-based $W'1$ (12.2 ± 2.7 kJ vs. 17.3 ± 5.4 kJ, respectively, t(13) = −3.98, P = 0.02) and $W'2$ (11.6 ± 2.7 kJ vs. 16.5 ± 4.8 kJ, respectively; t (13) = −3.93, p = 0.02). The mean difference in $W'1$ was −5.1 ± 4.8 kJ (95% CI, −7.86–9.14; [LOA], −14.5–4.3 kJ) and in $W'2$ it was −4.9 ± 4.7 kJ (95% CI, −7.58–8.94; [LOA], −14.0–4.2 kJ) (○ **Fig. 2**). The predication error associated with the laboratory-based and field-based estimates of CP/$W'$ was 1.9% (CP1), 2.5% (CP2) and for $W'$ it was 26.3% ($W'1$) and 27.6% ($W'2$). Analysis of [blood] lactate $(\text{mmol}\cdot\text{l}^{-1})$ revealed significantly higher concentrations for field-based testing when comparing the 100% TTE trial vs. the 7 min test (t (13) = −2.12, p = 0.035) and the 105% TTE trial vs. the 3 min test (t (13) = −2.36, p = 0.009), while the 80% TTE trial vs. the 12 min test did not result in a statistically significant but low p-value (0.054) (○ **Table 1**). ○ **Table 2** illustrates the differences in mean initial 10 s and 30 s power values for field and laboratory-based tests. ○ **Table 3** shows mean durations (± SD) and mean distances (± SD) for laboratory and field tests respectively. Ferguson et al. [11,12] 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.
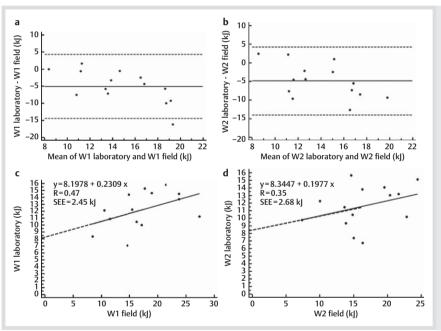
### Discussion
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A mean difference between laboratory- and field-derived estimates of CP of 0.2 ± 5.7 W, suggests that field testing might provide

**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**.

**Table 1** Group maximal [blood] lactate (mmol·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·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·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·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)

a valid estimate of CP in cycling. Results support those of Quod et al. [37], Kranenburg and Smith [28], and Galbraith et al. [16]. Using a magnitude-based analysis, Paton and Hopkins [33] identified that a change of 1.7 % in performance impacts on the chances of an elite road time trial cyclist winning an event. With an average SEE value for laboratory-based CP1/2 vs. field-based CP 1/2 of 1.9 % and 2.5 % respectively, the discrepancy between

the 2 measurement methods in the present study is deemed to be acceptable, considering that a group of elite cyclists would have likely produced lower biological variability.

While 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

| 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 |

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

| | Mean time elapsed seconds (minutes:seconds) | SD time elapsed seconds (minutes:seconds) | Mean distance covered (metres) | SD distance covered (metres) |
|---|---|---|---|---|
| Lab trials | | | | |
| 80 % MAP | 725.1 (12:05.1) | 141.1 (02:21.1) | – | – |
| 100 % MAP | 239.4 (03:59.4) | 48.0 (00:48.0) | – | – |
| 105 % MAP | 152.2 (02:32.2) | 29.8 (00:29.8) | – | – |
| Field trials | | | | |
| 3 min (180 s) | – | – | 1 857.7 | 156.8 |
| 7 min (420 s) | – | – | 4 118.4 | 232.6 |
| 12 min (720 s) | – | – | 7 030.4 | 260.9 |

**Table 3**  Mean durations (± SD) of laboratory-based TTE trials and field based set-time trials.

used for field testing provided no shelter and wind speeds above the $6 \, m \cdot s^{-1}$ criterion suggested by Swain [43] 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. Therefore results will need to be tested on different, and ideally larger, samples.

Another aspect of the data worthy of discussion concerns 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 s of the all tests. Testing in the field began from a standing start with an initial acceleration phase, while 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). It can be speculated that during the acceleration phase in the field subjects utilized a higher portion of type II muscle mass resulting in significantly higher power and blood [lactate] values [40, 45] 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. [41] 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, then 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). We acknowledge this limitation to our field-based approach and recognise that a rolling start with paced lap times might provide a more reliable estimate of $W'$.

CP has traditionally been estimated in the laboratory. Results of the present study, while 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. However the data presented above are from a small sample, and the authors advise a replication of the study, ideally with a larger subject group.

## Acknowledgements
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### References
1 *Atkinson G*, *Nevill AM*. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. Sports Med 1998; 26: 217–238
2 *Bertucci W*, *Duc S*, *Villerius V*, *Pernin JN*, *Grappe F*. Validity and reliability of the PowerTap mobile cycling powermeter when compared with the SRM Device. Int J Sports Med 2005; 26: 868–873
3 *Bertucci WM*, *Betik AC*, *Duc S*, *Grappe F*. Gross efficiency and cycling economy are higher in the field as compared with on an Axiom stationary ergometer. J Applied Biomech 2012; 28: 636–644
4 *Billat V*, *Renoux JC*, *Pinoteau J*, *Petit B*, *Koralsztein JP*. Reproducibility of running time to exhaustion at VO2max in subelite runners. Med Sci Sports Exerc 1994; 26: 254–257
5 *Blair SN*, *Painter P*, *Pate R*, *Smith K*, *Taylor C*. Resource manual for guidelines for exercise testing and prescription. Philadelphia: Lea & Febiger, 1988; 414–420
6 *Bland JM*, *Altman DG*. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986; 1: 307–310
7 *Carnevale TJ*, *Gaesser GA*. Effects of pedaling speed on the power-duration relationship for high-intensity exercise. Med Sci Sports Exerc 1991; 23: 242–246

8 *Dekerle J, Baron B, Dupont L, Vanvelcenaher J, Pelayo P.* Maximal lactate steady state, respiratory compensation threshold and critical power. Eur J Appl Physiol 2003; 89: 281–288

9 *Dekerle J, Sidney M, Hespel JM, Pelayo P.* Validity and reliability of critical speed, critical stroke rate, and anaerobic capacity in relation to front crawl swimming performances. Int J Sports Med 2002; 23: 93–98

10 *Denadai BS, Denadai ML.* Effects of caffeine on time to exhaustion in exercise performed below and above the anaerobic threshold. Braz J Med Biol Res 1998; 31: 581–585

11 *Ferguson C, Rossiter HB, Whipp BJ, Cathcart AJ, Murgatroyd SR, Ward SA.* Effect of recovery duration from prior exhaustive exercise on the parameters of the power-duration relationship. J Appl Physiol 2010; 108: 866–874

12 *Ferguson C, Whipp BJ, Cathcart AJ, Rossiter HB, Turner AP, Ward SA.* Effects of prior very-heavy intensity exercise on indices of aerobic function and high-intensity exercise tolerance. J Appl Physiol 2007; 103: 812–822

13 *Fukuba Y, Miura A, Endo M, Kan A, Yanagawa K, Whipp BJ.* The curvature constant parameter of the power-duration curve for varied-power exercise. Med Sci Sports Exerc 2003; 35: 1413–1418

14 Fukuba *Whipp BJ.* A metabolic limit on the ability to make up for lost time in endurance events. J Appl Physiol 1999; 87: 853–861

15 *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

16 *Galbraith A, Hopker J, Jobson SA, Passfield L.* A novel field test to determine critical speed. J Sport Med Doping Stud 2011; 1: 1–4

17 *Gardner AS, Stephens S, Martin DT, Lawton E, Lee H, Jenkins D.* Accuracy of SRM and power tap power monitoring systems for bicycling. Med Sci Sports Exerc 2004; 36: 1252–1258

18 *Harriss DJ, Atkinson G.* Update – Ethical standards in sport and exercise science research. Int J Sports Med 2011; 32: 819–821

19 *Hickey MS, Costill DL, McConell GK, Widrick JJ, Tanaka H.* Day to day variation in time trial cycling performance. Int J Sports Med 1992; 13: 467–471

20 *Hiyane WC, Simões HG, Sílvia C, Campbell G.* Critical velocity as a non-invasive method to estimate the lactate minimum velocity on cycling. Braz J Med Biol Res 2006; 12: 340–344

21 *Hopkins WG, Schabort EJ, Hawley JA.* Reliability of power in physical performance tests. Sports Med 2001; 31: 211–234

22 *Hopkins WA.* A new view on statistics. Internet Society for Sport Science 2000. Available at: http://www.sportsci.org/resource/stats/ Accessed 29 May 2013

23 *Housh DJ, Housh TJ, Bauge SM.* A methodological consideration for the determination of critical power and anaerobic work capacity. Res Q Exerc Sport 1990; 61: 406–409

24 *Jenkins D, Quigley BM.* Blood lactate in trained cyclists during cycle ergometry at critical power. Eur J Appl Physiol 1990; 61: 278–283

25 *Jenkins D, Quigley BM.* Endurance training enhances critical power. Med Sci Sports Exerc 1992; 24: 1283–1289

26 *Jeukendrup A, Saris WH, Brouns F, Kester AD.* A new validated endurance performance test. Med Sci Sports Exerc 1996; 28: 266–270

27 *Jobson SA, Nevill AM, Palmer GS, Jeukendrup AE, Doherty M, Atkinson G.* The ecological validity of laboratory cycling: Does body size explain the difference between laboratory- and field-based cycling performance? J Sports Sci 2007; 25: 3–9

28 *Kranenburg K, Smith DJ.* Comparison of critical speed determined from track running and treadmill tests in elite runners. Med Sci Sports Exerc 1996; 28: 614–618

29 *Krebs PS, Powers SK.* Reliability of laboratory endurance tests. Med Sci Sports Exerc 1989; 21: S 10

30 *MacDougall JD, Wenger HA* The purpose of physiological testing. In: Mac Dougall JD, Wenger HA, Green HJ. (eds.). Physiological Testing of the High-performance Athlete. Champaig, IL: Human Kinetics, 1991; 1–5

31 *McLellan TM, Cheung SS, Jacobs I.* Variability of time to exhaustion during submaximal exercise. Can J Appl Physiol 1995; 20: 39–51

32 *Palmer GS, Dennis SC, Noakes TD, Hawley JA.* Assessment of the reproducibility of performance testing on an air-braked cycle ergometer. Int J Sports Med 1996; 17: 293–298

33 *Paton C, Hopkins W.* Variation in performance of elite cyclists from race to race. Eur J Sport Sci 2006; 6: 25–31

34 *Poole DC, Ward SA, Gardner GW, Whipp BJ.* Metabolic and respiratory profile of the upper limit for prolonged exercise in man. Ergonomics 1988; 31: 1265–1279

35 *Poole DC, Ward SA, Whipp BJ.* The effects of training on the metabolic and respiratory profile of high-intensity cycle ergometer exercise. Eur J Appl Physiol 1990; 59: 421–429

36 *Pringle JSM, Jones AM.* Maximal lactate steady state, critical power and EMG during cycling. Eur J Appl Physiol 2002; 88: 214–226

37 *Quod M, Martin D, Martin J.* The power profile predicts road cycling MMP. Int J Sports Med 2010; 31: 397–401

38 *Schabort EJ, Hawley JA, Hopkins WG, Blum H.* High reliability of performance of well-trained rowers on a rowing ergometer. J Sports Sci 1999; 17: 627–632

39 *Schabort EJ, Hopkins WG, Hawley JA.* Reproducibility of self-paced treadmill performance of trained endurance runners. Int J Sports Sci 1998; 19: 48–51

40 *Sjödin B.* Lactate dehydrogenase in human skeletal muscle. Acta Physiol Scand Suppl 1976; 436: 1–32

41 *Skiba PF, Chidnok W, Vanhatalo A, Jones AM.* Modeling the expenditure and reconstitution of work capacity above critical power. Med Sci Sports Exerc 2012; 44: 1526–1532

42 *Smith JC, Hill DW.* Stability of parameter estimates derived from the power/time relationship. Can J Appl Physiol 1993; 18: 43–47

43 *Swain DP.* A model for optimizing cycling performance by varying power on hills and in wind. Med Sci Sports Exerc 1997; 29: 1104–1108

44 *Tanaka H, Bassett DR, Swenson TC, Sampedro RM.* Aerobic and anaerobic power characteristics of competitive cyclists in the United States. Int J Sports Med 1993; 14: 334–338

45 *Tesch P, Sjödin B, Karlsson J.* Relationship between lactate accumulation, LDH activity, LDH isozyme and fibre type distribution in human skeletal muscle. Acta Physiol Scand 1978; 103: 40–46

46 *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

47 *Wakayoshi K, Ikuta K, Yoshida T, Udo M, Moritani T, Mutoh Y, Miyashita M.* Determination and validity of critical velocity as an index of swimming performance in the competitive swimmer. Eur J Appl Physiol 1992; 64: 153–157

48 *Wilber RL, Moffatt RJ.* Influence of carbohydrate ingestion on blood glucose and performance in runners. Int J Sport Nutr 1992; 2: 317–327