UNIVERSITY OF LEEDS

This is a repository copy of *Maximal Sustained Isokinetic Power at Exercise Intolerance is not Critical Power*.

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/150143/

Version: Accepted Version

Article:

Yong, S, Swisher, AR, Ferguson, C orcid.org/0000-0001-5235-1505 et al. (1 more author) (2019) Maximal Sustained Isokinetic Power at Exercise Intolerance is not Critical Power. International Journal of Sports Medicine, 40 (10). pp. 631-638. ISSN 0172-4622

https://doi.org/10.1055/a-0946-1974

© Georg Thieme Verlag KG Stuttgart. This is an author produced version of a paper published in International Journal of Sports Medicine. Uploaded in accordance with the publisher's self-archiving policy.

Reuse
Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

White Rose
university consortium
Universities of Leeds, Sheffield & York

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Abstract

The asymptote of the hyperbolic power-duration relationship, critical power (CP), demarcates sustainable from non-sustainable exercise. CP is a salient parameter within the theoretical framework determining exercise tolerance. However, measuring CP is time consuming – typically 4 constant-power exercise tests to intolerance, or a 3-min all-out sprint is required. **PURPOSE** To determine whether 30 s of maximal isokinetic cycling, immediately following the limit of tolerance, approximates CP. **METHODS** Fifteen participants (7 women, 8 men, 23±5 yr, 71±12 kg, $\dot{V}O_{2peak}$ 4.39±1.04 $L.min^{-1}$; 61±9 $mL.kg.min^{-1}$) completed 4 constant supra-CP exercise tests to intolerance. Each test was followed immediately by a 30 s maximal isokinetic effort at 80 rpm. Mean isokinetic power was compared to the known CP. **RESULTS** Mean±SD CP was 159±47 W (CI_{95} 133, 185 W). Maximal isokinetic power immediately following intolerance was greater ($p<0.05$) than CP in all but one comparison (181±51 vs 159±47 W; $p>0.07$). However, this closest estimation, following the longest duration constant-power test, resulted in 21 W of mean bias and wide limits of agreement (±84 W). **CONCLUSIONS** Isokinetic power measured immediately following intolerance consistently overestimated critical power. Thus, an adjunct of 30 s maximal isokinetic cycling immediately following the limit of tolerance does not approximate critical power.

Abbreviations

CCC, Lin’s concordance correlation coefficient

CI_{95}, 95% confidence interval

CP, critical power

P_{iso}, isokinetic power

W′, curvature constant for the hyperbolic power-duration relationship

$\dot{V}O_{2max}$, maximal oxygen uptake

$\dot{V}O_{2peak}$, peak oxygen uptake

Introduction

Tolerance to high-intensity exercise is characterised by a hyperbolic power-to-tolerable-duration relationship [16,25]. The relationship is defined by two parameters – the curvature constant, termed W′, and an asymptote, termed critical power [25]. Critical power demarcates sustainable from non-sustainable exercise. Both parameters are essential for a rigorous characterization of exercise tolerance. Combined with ramp-incremental exercise to measure lactate threshold and $\dot{V}O_{2peak}$, critical power provides the third metabolic threshold to characterise the exercise intensity domains [30]. As habitual physical activity and exercise tolerance are such strong predictors of mortality in health and disease [21,23,24], measuring critical power can provide vital prognostic information and an outcome variable for rehabilitation [31] – albeit with barriers to widespread use as measurement of critical power is cumbersome.

Characterizing the power-duration relationship is time consuming and requires repeated exercise efforts to the limit of tolerance – typically 4 constant power exercise tests to intolerance on separate days are required [19]. Thus, alternatives have been introduced to estimate either critical power, W′, or both in a single laboratory visit. These include the 3 min 'all-out' exercise test with or without a prior ramp in the same laboratory visit [4,9,10,29]. Additionally, a ramp-sprint test was devised that comprises a 3 min 'all-out' exercise bout immediately following the limit of tolerance to ramp exercise [20]. Interestingly, the profile of supra-critical-power exercise (ramp incremental, variable power such as the 3 min all-out test, constant power, etc.) appears to be of little consequence for depletion of W′ [4,6,20], providing important flexibility in designing testing formats. The ramp-sprint test provides lactate threshold, $\dot{V}O_{2max}$, and critical power in one laboratory visit with the premise being prior depletion of W′ during the ramp. This is a small modification on the 3 min all-out test that incorporates simultaneous depletion of W’ during the 3 min effort. Thus, the highest power that is sustainable following W′ depletion is critical power [7]. However, the sustained exertion during the 3 min sprint-type ‘all-out’ exercise, either on its own, or following maximal ramp-incremental exercise can be a barrier for some participants or patients. In addition, participants need to be highly motivated to successfully complete the exercise test such that the measure of critical power is valid – this includes maintenance of $\dot{V}O_2 > 95\%$ of $\dot{V}O_{2max}$ as a quality control criterion [18]. These factors are the greatest barriers to implementing critical power measurements into the clinical physiology laboratory. Attempts to shorten the duration of ‘all-out’ tests (without prior depletion of W′) have resulted in overestimation of critical power [3,11].

At the limit of tolerance to supra-critical-power exercise, and thus after depletion of W′, all-out sprint exercise approximates critical power [20]. Importantly, this appears to be the case with as little as 30-60 s of maximal effort [20]. During the ramp-sprint test, however, there is an inherent delay for power to resolve at a ‘steady state’ following the initiation of the all-out sprint. This is due to 1) substantial effort (and time) required to accelerate the ergometer flywheel in this cadence-dependent test format (~80rpm depending on the linear factor chosen), and 2) overcoming the symptoms of having just reached the tolerable limit. In addition, the linear factor must be estimated and can result in the critical power estimate occurring at a cadence different from the participant’s normal operating cadence. This is important, as contraction velocity will directly affect the measurement of critical power [1]. This, in turn limits W′ depletion during the 3-min test when performed in isolation as the power will be lower throughout.

By circumventing this adjustment period by using an instantaneous switch to isokinetic ergometry [5,8,12,14], it may be possible to measure an approximation of critical power in less than 30 s of 'all-out' sprint type exercise. The switch to isokinetic cycling provides no electromagnetic braking resistance in returning to the appropriate flywheel velocity as no braking is applied below the target velocity. This approach also eliminates the requirement to estimate a linear factor. This duration of maximal effort following intolerance might be brief enough to allow for estimation of this parameter for clinical application. However, the intramuscular forces differ during cadence-independent and isokinetic cycling, and therefore the two paradigms may elicit dissimilar metabolic responses and even different W′ and critical power [1,10]. Whether the discordance with isokinetic measurements extends to relatively short bouts to estimate critical power has not been tested. Thus, we aimed to determine whether 30 s of maximal isokinetic power measured immediately following the limit of tolerance approximates critical power. We hypothesized that the isokinetic power would be in close agreement with critical power measured from the multi-bout approach.

Materials and Methods

Participants

Fifteen participants (7 women, 8 men, 23±5 yr, 71±12 kg) took part in the study. Written informed consent was obtained and the San Diego State University Institutional Review Board approved the protocol. The study protocol and manuscript meets the standards outlined by the Int J Sports Med [15].

Ramp-incremental exercise

Volunteers completed a ramp-incremental exercise test (20-25 $W.min^{-1}$) to the limit of tolerance. The test was completed using a computer-controlled, electromagnetically-braked ergometer in the hyperbolic mode and thus cadence-independent (Excalibur, Lode BV, NL). Participants were instructed to maintain a cadence of ~70-90 rpm. The limit of tolerance was defined as being unable to maintain a pedalling cadence above 55 rpm, despite strong verbal encouragement.

Constant power and isokinetic efforts

The power-duration relationship for each participant was characterised using 4 constant power tests to the limit of tolerance. Each test was completed on separate days. As a starting point, the first constant power test was estimated by subtracting 1 min worth of ramp increment from the peak power measured during the ramp-incremental test [28]. This yields an exercise tolerance of ~6 min and provides a basis for subsequent adjustments in test power.

Each of the 4 constant power exercise tests were immediately followed by a maximal isokinetic effort at 80 rpm for 30 s. Mean isokinetic power (P_{iso}) over the final 20, 10, and

5 s was compared to the critical power asymptote (CP) determined from the multi-bout approach [19]. That is, for each participant, power and tolerable duration were used to establish hyperbolic curvature constant and asymptote:

$$W' = t(P\text{-}CP) \qquad \text{Equation 1}$$

where W′ is the curvature constant, t is tolerable duration, P is power and CP is the critical power asymptote. For simplicity, the CP and W′ parameters were determined from linear regression by fitting P as a function of (1/t):

$$P = W'(1/t) + CP \qquad \text{Equation 2}$$

Thus, each participant completed 4 maximal isokinetic efforts lasting 30 seconds (with 3 different bin averages for isokinetic power analysis for each test – bin averages were 5, 10, 20 s in duration) for 12 potential comparisons to critical power. The first 10 s of each isokinetic effort were discarded to eliminate a transient excursion of power due to the flywheel not being constrained at precisely the target velocity. This was also done to avoid including a power spike resulting from the flywheel rapidly accelerating and delivering its inertia to the target velocity.

Ergometry

The computer-controlled electromagnetically-braked cycle ergometer (Excalibur Sport PFM, Lode BV, Groningen, NL) was instrumented with force transducers in the bottom bracket spindle. Left and right torque (Nm) was measured independently (peak force 2000 N, < 0.5 N resolution and measurement uncertainty of < 3%). Angular velocity of the crank (rad.s^{-1}) was measured by three independent sensors sampling in series with a resolution of 2° (measurement uncertainty of < 1%). During isokinetic efforts, power was calculate d as a mean for each crank revolution. Mean P_{iso} was calculated over the final 20, 10, and 5 s of isokinetic effort.

Cardiopulmonary Measurements

Respired gases and ventilation were measured breath-by-breath with a commercial metabolic measurement system (VMax Spectra, CareFusion, San Diego, CA USA). The system was calibrated immediately prior to each experiment. A 3 L syringe (Hans Rudolph Inc., Shawnee, KS, USA) was used to calibrate the mass flow sensor from ~0.2 to 8.0 $L.s^{-1}$, mimicking flow rates expected at rest and during exercise. The CO_2 and O_2 analysers were calibrated using gases of known concentrations (O_2 26.0% and 16.0%; CO_2 0.0% and 4.0%).

Statistical analyses

Means were compared, where appropriate, with t-tests. Statistical significance was determined at $p<0.05$. Data are presented as mean±SD, and, where appropriate, the 95% confidence interval (CI_{95}) is included. CI_{95} for linear regression estimation (for critical power and W′) were calculated to provide forecasted values, ŷ, of x:

$$\hat{y} \pm t_{crit} \cdot s.e. \qquad \text{Equation 3}$$

where

$$s.e. = s_{yx}\sqrt{\frac{1}{n}+\frac{(x-\bar{x})^2}{SS_x}} \qquad \text{Equation 4}$$

Mean bias and limits of agreement were calculated using the method of Bland & Altman [2]. Further, agreement was examined using Lin's concordance correlation coefficient (CCC).

Results

$\dot{V}O_{2peak}$ (the highest 20 s mean) was 4.39±1.04 $L.min^{-1}$ or 61±9 $mL.kg.min^{-1}$. $\dot{V}O_{2peak}$ at the limit of tolerance during ramp-incremental exercise and all of the constant power tests to intolerance were similar ($p>0.05$), confirming $\dot{V}O_{2max}$ was attained in all tests [26]. Critical power, measured using 4 constant power tests, was 159±47 W (CI_{95} 133, 185 W). W′ was 15.5±8.5 kJ (CI_{95} 10.7, 20.2 kJ). Actual work done above CP was not different ($p>0.4$) from W′ for any of the four constant power trials (15.4±8.8, 15.8±8.3, 15.2±9.2, and 15.0±8.5 kJ, respectively). The confidence limits were determined in relation to the fit of each participant's power-duration relationship, and the corresponding CI_{95} for critical power were (lower CI: 140±50 W; upper CI: 178±47 W). Thus, the span of the CI_{95} was 38±26 W.

A representative power-duration relationship and responses from a single constant power test are displayed in Fig 1 (filled data at ~150 W, Panels A, B & C). Fig 1 Panel C shows the constant power test to intolerance with the addition of a 30 s maximal isokinetic effort (grey dash) immediately following intolerance. Panel D shows the final 20 s of the P_{iso} bout with the critical power asymptote identified from characterization of the power-duration relationship (Fig 1 A) demarcated by the dashed line. In Panel D, each grey datum represents 1 crank revolution mean.

20 s means of isokinetic data

The final 20 s of the isokinetic effort yielded high mean bias (52±7 W) regardless of constant power test duration (Fig 2). Limits of agreement were also wide with a mean span of 220±46 W (Fig 2). The closest estimation of critical power was that of the isokinetic effort following the lowest power, longest duration test: mean P_{iso} was 203±67 W ($p<0.05$ vs the multi-bout critical power of 159±47 W); mean bias was 44 W and limits of agreement were ±106 W (Fig 2, Panel D). Mean work done above CP during the 20 s isokinetic effort across each of the 4 trials was 1.0±1.1 kJ. For comparison, true W′ as measured with the multi-bout approach was 15.5±8.5 kJ (CI_{95} 10.7, 20.2 kJ).

10 s means of isokinetic data

The final 10 s of the isokinetic effort yielded high mean bias (41±5 W) no matter the constant power test duration (Fig 3). Limits of agreement were also wide with a mean span of 189±37 W (Fig 3). The closest estimation of critical power was that of the isokinetic effort following the longest duration test, as it was when using the final 20 s means. Mean P_{iso} during this test was 193±59 W ($p<0.05$ vs actual critical power of 159±47 W). Mean bias was 33 W and limits of agreement were ±90 W (Fig 3, Panel D).

5 s means of isokinetic data

The final 5 s of the isokinetic effort showed the lowest mean bias (33±8 W) and was consistent across test duration (Fig 4). Limits of agreement were still wide with a mean span of 182±38 W (Fig 4). The closest estimation of critical power was again that of the isokinetic effort following the longest duration test. Mean P_{iso} during this test was 181±51 W and not statistically different from actual critical power ($p>0.07$ vs actual critical power of 159±47 W). Mean bias was 21 W and limits of agreement were ±84 W (Fig 4, Panel D). Scatterplots are provided in Fig 5 for all comparisons to critical power and CCC is included in each plot.

Discussion

We aimed to test whether a 30 s maximal isokinetic effort immediately following the limit of tolerance approximates critical power. We hypothesized that this short format test would provide an alternative to measuring critical power with multiple laboratory visits [19,25] or longer, more arduous exercise test formats, e.g. [3,4,10,11,20]. Our rationale was based on W′ depletion at intolerance and that the highest power subsequently sustainable would be critical power [7,20]. To the contrary, we found that 30 s of maximal isokinetic exercise was not sufficient to measure critical power. Our protocol resulted in an overestimation of critical power (at least 20 W) and unacceptably wide limits of agreement when comparing mean isokinetic power and the multi-bout approach (four independent constant power tests). Further, participants were able to complete more than 1 kJ of additional work above critical power during the isokinetic effort following the limit of tolerance. As an additional measure of agreement, we have reported Lin's CCC. The values are similar to that from the Bland-Altman analysis in that the coefficients range from weak to modest (0.33 – 0.64; Fig 5).

Is the criterion an appropriate *'gold standard' reference?*

An important component of our comparison was the establishment of a rigorous estimate of critical power. Similar to our previous reports [20], the CI_{95} for critical power measurement (within participant) was narrow. In our current experiment the span of CI_{95} was 38±26 W. Therefore, we are confident that the much wider limits of agreement in Figs 2-4 are due to the shortcomings of using isokinetic power, rather than a large influence from errors in the criterion measure.

Is the P_{iso} pattern trending toward critical power?

Some participants show a 30 s P_{iso} pattern similar to that presented in Fig 1, Panel D where it appears as though power is still in the process of resolving toward critical power. From the final 20, 10, and 5 s time bins this appears to be the case across the participant group: mean bias falls, and the limits of agreement improve to some extent. However, any additional duration while producing > critical power would also result in even larger W′ overestimation in reference to the multi-bout measurement, as discussed above. The natural inclination is to want to extend the test further, although our original intent was trying to find a solution with a substantially shorter effort to be more appropriate for a clinical physiology laboratory – defining just how long the test need be is clearly up for debate. It appears as though this is not possible, at least to any extent shorter than the 30-60 s of effort already presented during the all-out portion of the ramp-sprint test [20]. As with many measurements, shortcuts are often not possible without compromising precision and accuracy. Thus, independent visits, 3 min all-out test, or ramp-sprint test formats appear to be optimized in their current format. As discussed above, and in the original paper [20], the maximal power possible following the limit of tolerance often stabilizes between 30 and 60 s. Thus, the test might be offered in a manner where it can be terminated early (i.e. at 60 s rather than 3 min) depending on the characteristics of power output [20]. However, this has yet to be tried systematically and especially needs feasibility and validation studies in vulnerable populations such as patients with chronic cardiopulmonary disease. Whether or not symptom limitations will allow such a patient to fully deplete W′ by the limit of tolerance is also a concern. This is particularly true for patients with obstructive disease. It is more likely in those cases that the limit of tolerance and CP are constrained by maximal voluntary ventilation [22].

Another interesting question is whether or not we expect isokinetic power to resolve at CP, given enough time. Perceptually, the cycling is far different to a fixed resistance mode, but it would seem the bioenergetic determinants would still constrain the CP at the same output. Clearly only one of the two factors is being constrained (angular velocity), so it would seem that the variations in torque should be sufficient to apply the measurement. However, without extended durations in the isokinetic mode, we can only speculate.

What explains the capacity for supra-critical-power exercise following the limit of tolerance?

Similar to our experiments and others showing a small, short-term locomotor power reserve in healthy people (on the scale of 5 s) following the limit of tolerance [5,8,17], there appears to be some capacity to sustain exercise above critical power after reaching intolerance. Again, it is important to note the time scale of ≤ 30 s in this case. Still, this is surprising considering the prior depletion of W′ and the additional work done on the scale of ~7% of W′.

Our study design was intended to minimize recovery duration between the limit of tolerance and P_{iso} measurement. Further, by switching from hyperbolic ergometry to isokinetic, the flywheel inertia and braking force was minimized as much as possible (as opposed to accelerating the flywheel under braking using the linear resistance mode [4,20]). The time delay from intolerance to maximal isokinetic effort is not zero but typically 2-3 s. Therefore, only minimal recovery in muscle metabolites (with time constants on the scale of 30 s) is possible. However, as the recovery time constant of W′ is well above 200 or 300 s [13,27], it seems very unlikely that this is sufficient to explain power generated substantially above critical power following intolerance. Even with a liberal estimate of a half time of 200 s, and a 5 s delay, the resulting W′ recovery is in the order of 250 J (<2% recovered). The work done above critical power in the final 20 s was ~4x this amount of work. Each of our Bland-Altman plots also demonstrate a systematic bias such that the agreement between the ‘traditional’ and isokinetic measurement is worse in participants with a high critical power. Conversely, we do not know if patients with low critical power might show better agreement than that of their young/healthy counterparts. Interestingly, this bias argues against an issue of extremely high intramuscular pressures negatively affecting power production – those with high critical power had even greater power production during the isokinetic trial than volunteers with more modest critical power.

We do want to note the substantial difference between supra-critical-power power generation in our present paper and that of much shorter supra-task power ‘reserve’ on the scale of a few seconds [17]. The neuromuscular short-term capacity (5 s) that others and we have reported is unlikely to be defined by the same bioenergetic constraints that the 30 s effort is subject to. Nonetheless, the mechanisms that allow for supra-critical-power exercise to be sustained during this 30 s isokinetic effort are unknown.

Conclusions

Isokinetic power measured immediately following the limit of tolerance consistently overestimated critical power. The closest estimation resulted in 21 W mean bias with wide limits of agreement. Thus, brief maximal isokinetic power (30 s) immediately following the limit of tolerance does not approximate critical power.

Competing Interests

Authors have no competing interests.

Funding

SY and ARS were supported by the SDSU Summer Undergraduate Research Program.

Author Contributions

CF and DTC conceived of, and designed the experiments. SY, ARS, and DTC acquired and analysed the data. SY, ARS, CF, and DTC interpreted the data. SY, ARS, and DTC drafted the manuscript. CF revised the manuscript critically for important intellectual content. All authors approved the final version of the manuscript.

Acknowledgements

Thank you to our volunteers for your time and dedication.

Figure Legends

Figure 1. Single participant power-duration relationship and representative maximal isokinetic power (P_{iso}) immediately following the limit of tolerance. Dashed line represents the critical power asymptote. **A:** Hyperbolic power-duration relationship. **B:** Power-1/duration relationship from the same participant where y-intercept is critical power asymptote. **C:** Representative constant power test at 150 W (filled symbols from Panel A and B) to intolerance immediately followed by the isokinetic effort (grey dash). **D:** Isolation of the final 20 s of the isokinetic effort (30 s in total duration) immediately following intolerance. This panel shows the data from the same representative participant in previous panels. In this case, the power appears to be trending toward critical power.

Figure 2. Bland-Altman plots for agreement between the final 20 s of maximal isokinetic power (P_{iso}) following the limit of tolerance and critical power (CP). Solid line represents mean bias. Dotted lines are upper and lower limits of agreement (mean bias ± 1.96 SD). **A:** P_{iso} following highest constant power (242±62 W) test to intolerance - therefore shortest duration. **B:** P_{iso} following 220±62 W to intolerance. **C:** P_{iso} following 194±58 W

to intolerance. **D:** P_{iso} following lowest constant power (190±56 W) test to intolerance - therefore longest duration.

Figure 3. Bland-Altman plots for agreement between the final 10 s of maximal isokinetic power (P_{iso}) following the limit of tolerance and critical power (CP). Solid line represents mean bias. Dotted lines are upper and lower limits of agreement (mean bias ± 1.96 SD). **A:** P_{iso} following highest constant power (242±62 W) test to intolerance - therefore shortest duration. **B:** P_{iso} following 220±62 W to intolerance. **C:** P_{iso} following 194±58 W to intolerance. **D:** P_{iso} following lowest constant power (190±56 W) test to intolerance - therefore longest duration.

Figure 4. Bland-Altman plots for agreement between the final 5 s of maximal isokinetic power (P_{iso}) following the limit of tolerance and critical power (CP). Solid line represents mean bias. Dotted lines are upper and lower limits of agreement (mean bias ± 1.96 SD). **A:** P_{iso} following highest constant power (242±62 W) test to intolerance - therefore shortest duration. **B:** P_{iso} following 220±62 W to intolerance. **C:** P_{iso} following 194±58 W to intolerance. **D:** P_{iso} following lowest constant power (190±56 W) test to intolerance - therefore longest duration.

Figure 5. Scatterplots of all critical power comparisons to P_{iso} estimates. Lin's concordance correlation coefficient (CCC) is provided in each panel. Top, middle, and bottom rows are means from 20, 10, and 5 s P_{iso} bins. Line is y=x.

References

1. Barker T, Poole DC, Noble ML, Barstow TJ. Human critical power-oxygen uptake relationship at different pedalling frequencies. Exp Physiol 2006; 91: 621-632

2. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986; 1: 307-310

3. Brickley G, Dekerle J, Hammond AJ, Pringle J, Carter H. Assessment of maximal aerobic power and critical power in a single 90-s isokinetic all-out cycling test. Int J Sports Med 2007; 28: 414-419

4. Burnley M, Doust JH, Vanhatalo A. A 3-min all-out test to determine peak oxygen uptake and the maximal steady state. Med Sci Sports Exerc 2006; 38: 1995-2003

5. Cannon DT, Coelho AC, Cao R, Cheng A, Porszasz J, Casaburi R, Rossiter HB. Skeletal muscle power and fatigue at the tolerable limit of ramp-incremental exercise in COPD. J Appl Physiol (1985) 2016; 121: 1365-1373

6. Chidnok W, Dimenna FJ, Bailey SJ, Wilkerson DP, Vanhatalo A, Jones AM. Effects of pacing strategy on work done above critical power during high-intensity exercise. Med Sci Sports Exerc 2013; 45: 1377-1385

7. Coats EM, Rossiter HB, Day JR, Miura A, Fukuba Y, Whipp BJ. Intensity-dependent tolerance to exercise after attaining V(O2) max in humans. J Appl Physiol 2003; 95: 483-490

8. Coelho AC, Cannon DT, Cao R, Porszasz J, Casaburi R, Knorst MM, Rossiter HB. Instantaneous quantification of skeletal muscle activation, power production, and fatigue during cycle ergometry. J Appl Physiol (1985) 2015; 118: 646-654

9. Constantini K, Sabapathy S, Cross TJ. A single-session testing protocol to determine critical power and W'. Eur J Appl Physiol 2014; 114: 1153-1161

10. Dekerle J, Barstow TJ, Regan L, Carter H. The critical power concept in all-out isokinetic exercise. Journal of science and medicine in sport 2014; 17: 640-644

11. Dekerle J, Williams C, McGawley K, Carter H. Critical power is not attained at the end of an isokinetic 90-second all-out test in children. J Sports Sci 2009; 27: 379-385

12. Ferguson C, Cannon DT, Wylde LA, Benson AP, Rossiter HB. Power-velocity and power-efficiency implications in the limitation of ramp incremental cycle ergometry. J Appl Physiol (1985) 2015, DOI: 10.1152/japplphysiol.01067.2015: jap 01067 02015

13. 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 (1985) 2010; 108: 866-874

14. Ferguson C, Wylde LA, Benson AP, Cannon DT, Rossiter HB. No reserve in isokinetic cycling power at intolerance during ramp incremental exercise in endurance-trained men. J Appl Physiol (1985) 2016; 120: 70-77

15. Harriss DJ, Macsween A, Atkinson G. Standards for Ethics in Sport and Exercise Science Research: 2018 Update. Int J Sports Med 2017; 38: 1126-1131

16. Hill AV. The Physiological Basis of Athletic Records. Nature 1925; 118: 544-548

17. Hodgson MD, Keir DA, Copithorne DB, Rice CL, Kowalchuk JM. Power reserve following ramp-incremental cycling to exhaustion: implications for muscle fatigue and function. J Appl Physiol (1985) 2018, DOI: 10.1152/japplphysiol.00722.2017:

18. Jones AM, Vanhatalo A, Burnley M, Morton RH, Poole DC. Critical power: implications for determination of V O2max and exercise tolerance. Med Sci Sports Exerc 2010; 42: 1876-1890

19. Moritani T, Nagata A, deVries HA, Muro M. Critical power as a measure of physical work capacity and anaerobic threshold. Ergonomics 1981; 24: 339-350

20. Murgatroyd SR, Wylde LA, Cannon DT, Ward SA, Rossiter HB. A 'ramp-sprint' protocol to characterise indices of aerobic function and exercise intensity domains in a single laboratory test. Eur J Appl Physiol 2014; 114: 1863-1874

21. Myers J, Prakash M, Froelicher V, Do D, Partington S, Atwood JE. Exercise capacity and mortality among men referred for exercise testing. N Engl J Med 2002; 346: 793-801

22. Neder JA, Jones PW, Nery LE, Whipp BJ. Determinants of the exercise endurance capacity in patients with chronic obstructive pulmonary disease. The power-duration relationship. Am J Respir Crit Care Med 2000; 162: 497-504

23. Paffenbarger RS, Jr., Hyde RT, Wing AL, Hsieh CC. Physical activity, all-cause mortality, and longevity of college alumni. N Engl J Med 1986; 314: 605-613

24. Paffenbarger RS, Jr., Hyde RT, Wing AL, Lee IM, Jung DL, Kampert JB. The association of changes in physical-activity level and other lifestyle characteristics with mortality among men. N Engl J Med 1993; 328: 538-545

25. Poole DC, Burnley M, Vanhatalo A, Rossiter HB, Jones AM. Critical Power: An Important Fatigue Threshold in Exercise Physiology. Med Sci Sports Exerc 2016; 48: 2320-2334

26. Poole DC, Jones AM. Measurement of the maximum oxygen uptake Vo2max: Vo2peak is no longer acceptable. J Appl Physiol (1985) 2017; 122: 997-1002

27. Skiba PF, Fulford J, Clarke DC, Vanhatalo A, Jones AM. Intramuscular determinants of the ability to recover work capacity above critical power. Eur J Appl Physiol 2015; 115: 703-713

28. van der Vaart H, Murgatroyd SR, Rossiter HB, Chen C, Casaburi R, Porszasz J. Selecting Constant Work Rates for Endurance Testing in COPD: The Role of the Power-Duration Relationship. COPD 2014; 11: 267-276

29. 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

30. Whipp BJ. Domains of aerobic function and their limiting parameters. In: Steinacker JM, Ward, S.A. ed, The physiology and pathophysiology of exercise tolerance. New York: Plenum; 1996: 83-89

31. Whipp BJ, Ward SA. Quantifying intervention-related improvements in exercise tolerance. Eur Respir J 2009; 33: 1254-1260

Figure 1

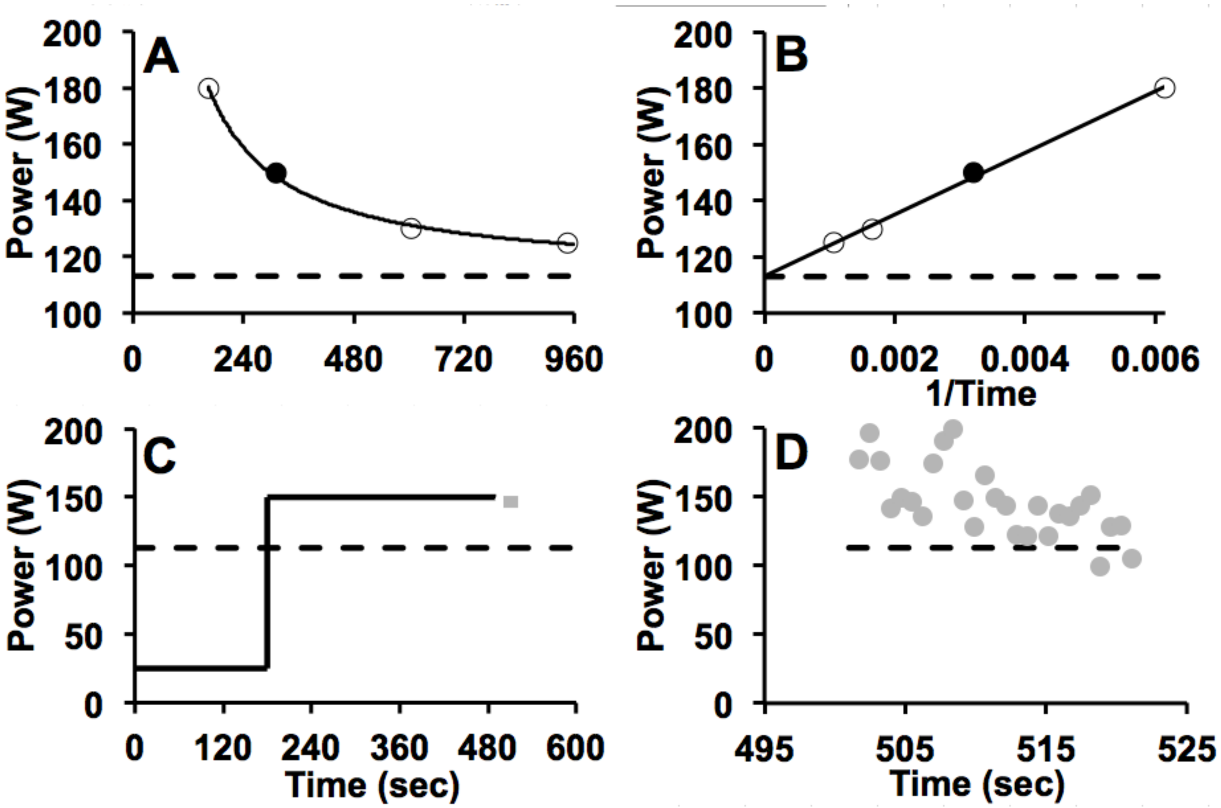

A
Power (W)
200
180
160
140
120
100
0
240
480
720
960
B
Power (W)
200
180
160
140
120
100
0
0.002
0.004
0.006
1/Time
C
Power (W)
200
150
100
50
0
0
120
240
360
480
600
Time (sec)
D
Power (W)
200
150
100
50
0
495
505
515
525
Time (sec)

Figure 2

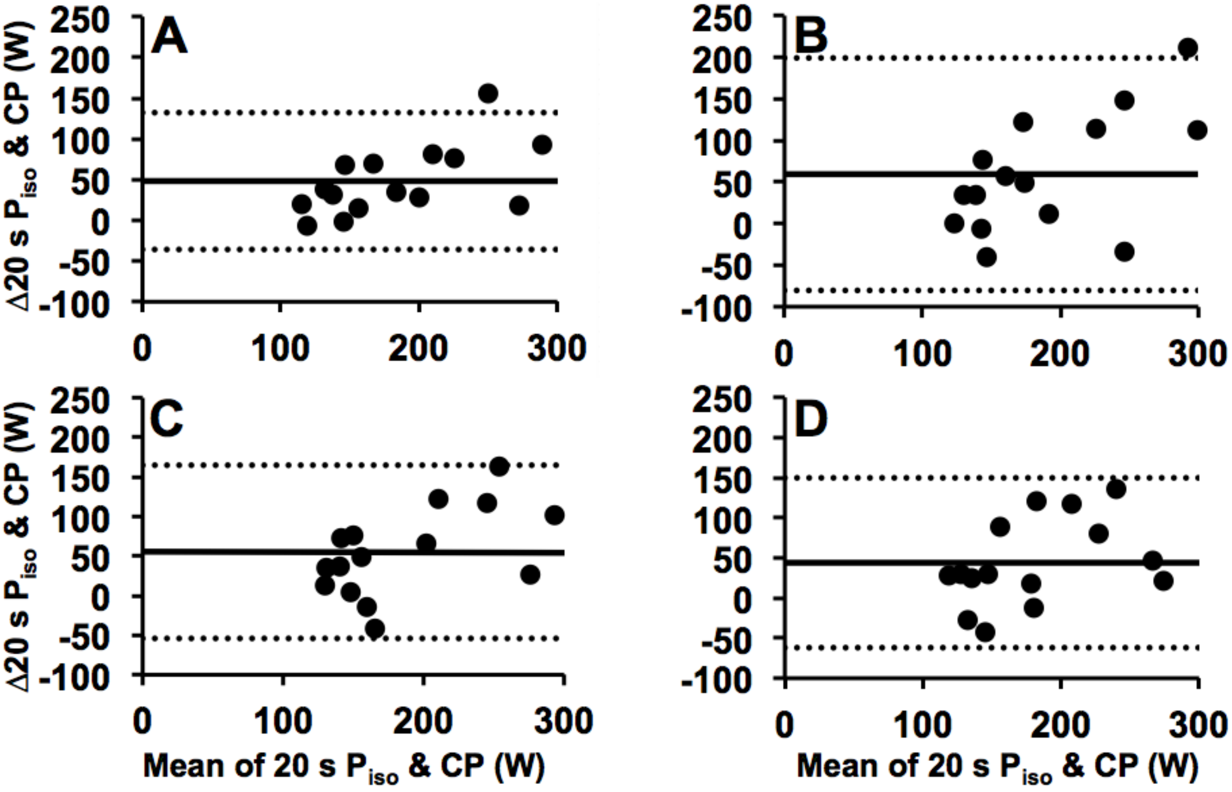

A
B
C
D
Δ20 s P_{iso} & CP (W)
Mean of 20 s P_{iso} & CP (W)
250
200
150
100
50
0
-50
-100
0
100
200
300

Figure 3

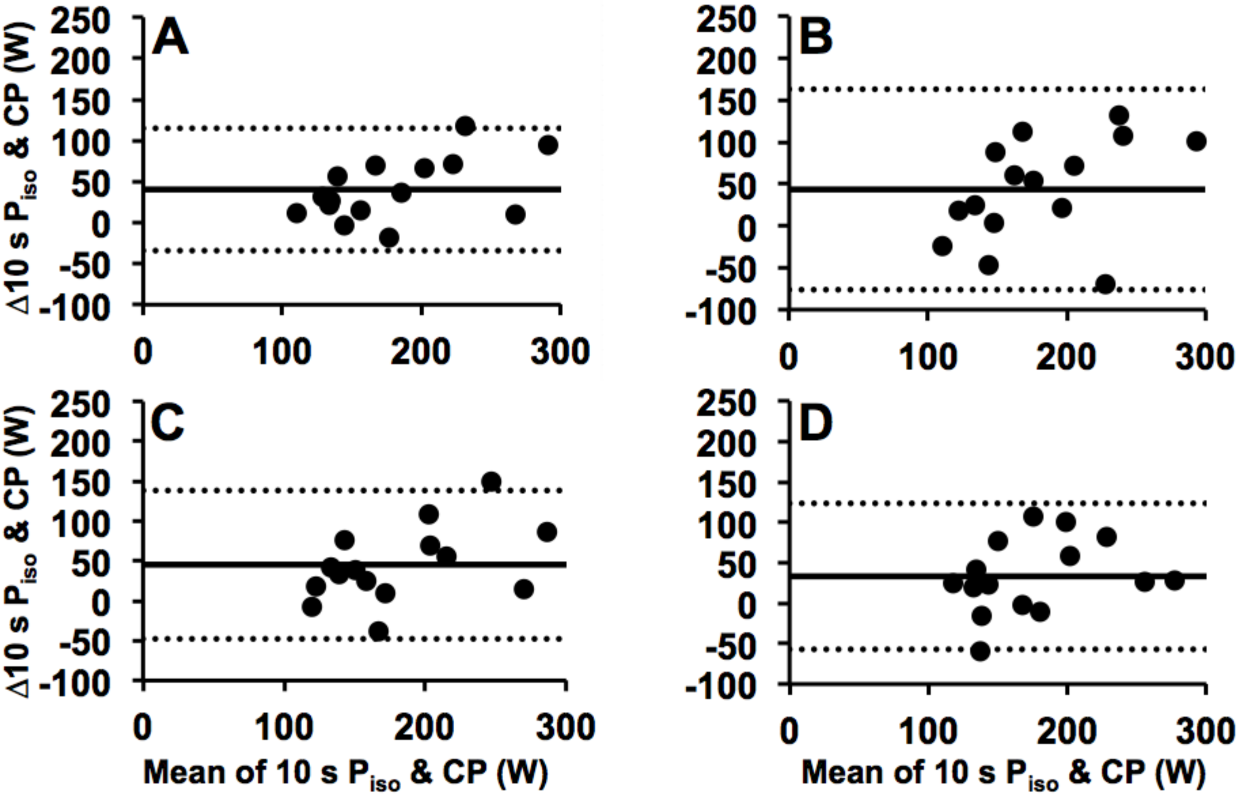

A
B
C
D
Δ10 s P_{iso} & CP (W)
Mean of 10 s P_{iso} & CP (W)
250
200
150
100
50
0
-50
-100
0
100
200
300

Figure 4

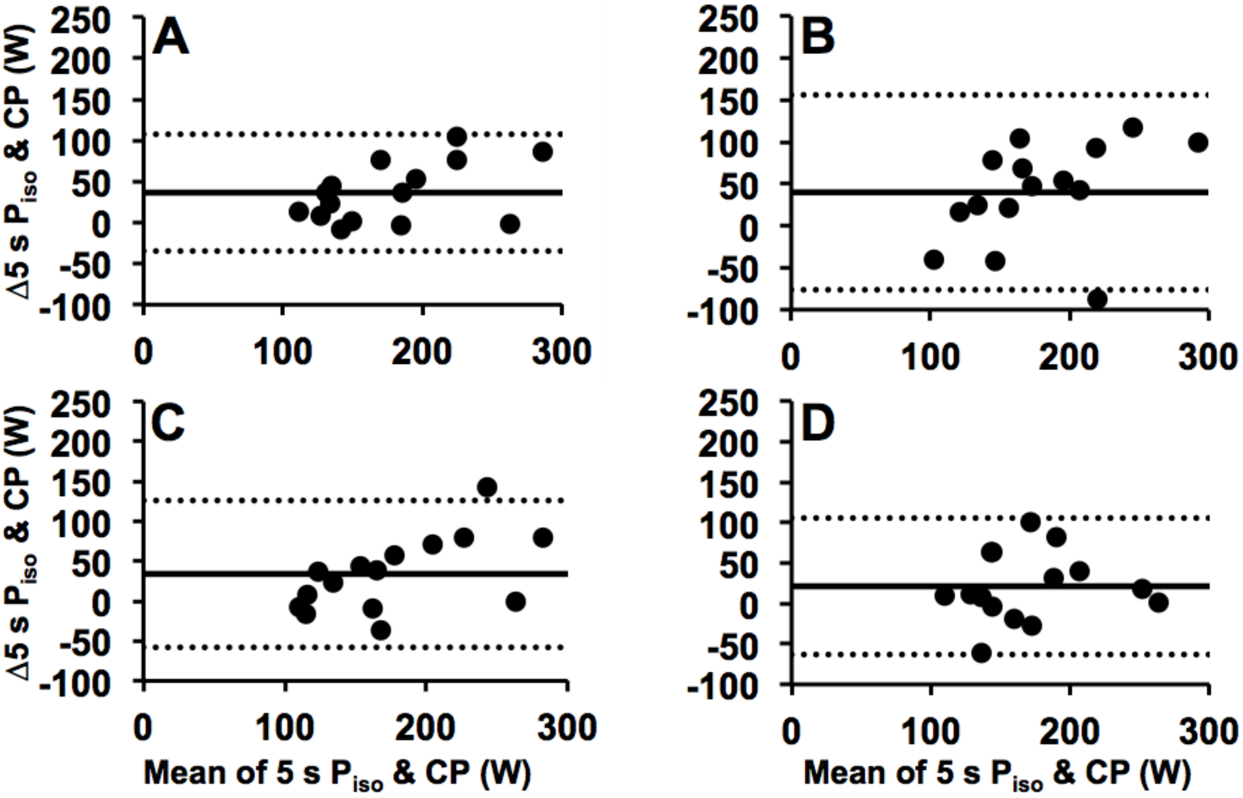
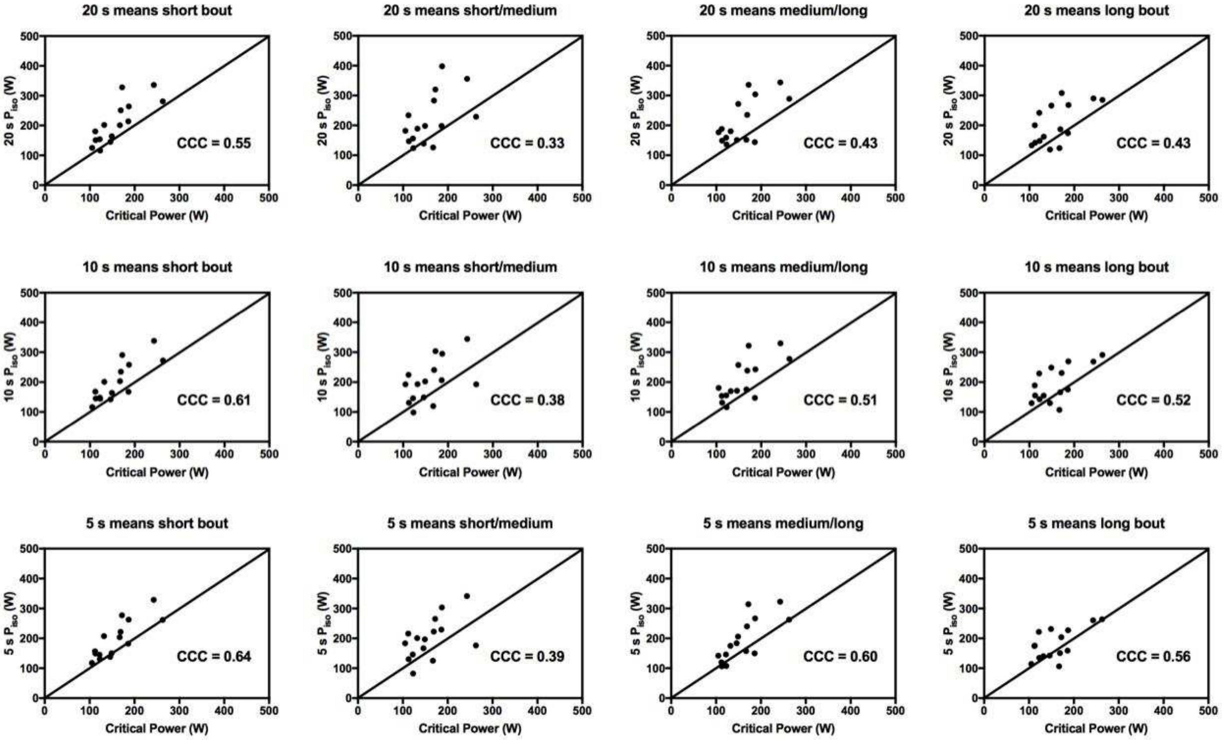

A
B
C
D
Δ5 s P_{iso} & CP (W)
250
200
150
100
50
0
-50
-100
0
100
200
300
Mean of 5 s P_{iso} & CP (W)

Figure 5


20 s means short bout
20 s means short/medium
20 s means medium/long
20 s means long bout
20 s P_{iso} (W)
CCC = 0.55
CCC = 0.33
CCC = 0.43
CCC = 0.43
10 s means short bout
10 s means short/medium
10 s means medium/long
10 s means long bout
10 s P_{iso} (W)
CCC = 0.61
CCC = 0.38
CCC = 0.51
CCC = 0.52
5 s means short bout
5 s means short/medium
5 s means medium/long
5 s means long bout
5 s P_{iso} (W)
CCC = 0.64
CCC = 0.39
CCC = 0.60
CCC = 0.56
Critical Power (W)
0
100
200
300
400
500