Jason C Bartram, Dominic Thewlis, David T Martin, Kevin I Norton

Predicting critical power in elite cyclists: questioning validity of the 3-min All-out test

International Journal of Sports Physiology and Performance, 2016; OnlinePubl:1-19

Section: Original Investigation

Article Title: Predicting Critical Power in Elite Cyclists: Questioning Validity of the 3-min All-out Test

Authors: Jason C Bartram[1,2], Dominic Thewlis[1], David T Martin[3], and Kevin I Norton[1]

Affiliations: [1]University of South Australia, Adelaide, SA, Australia. [2]Cycling Australia. [3]Australian Institute of Sport.

Journal: *International Journal of Sports Physiology and Performance*

Acceptance Date: October 6, 2016

DOI: http://dx.doi.org/10.1123/ijspp.2016-0376

“Predicting Critical Power in Elite Cyclists: Questioning Validity of the 3-min All-out Test”
by Bartram JC, Thewlis D, Martin DT, Norton KI
International Journal of Sports Physiology and Performance

Predicting critical power in elite cyclists: Questioning validity of the 3-min All-out test

Original Investigation

Jason C Bartram[1,2]

Dominic Thewlis[1]

David T Martin[3]

Kevin I Norton[1]

University of South Australia[1]

Cycling Australia[2]

Australian Institute of Sport[3]

Corresponding Author:
Jason Bartram
University of South Australia
School of Health Sciences
GPO Box 2471
Adelaide, SA 5001 Australia
Phone: (08) 8302 2425
Fax: (08) 8302 2766
jason.bartram@mymail.unisa.edu.au

Running Head: Critical power in elite cyclists

Abstract word count: 249

Text only word count: 2713

Number of figures and tables: 5

ABSTRACT

Purpose: New applications of the critical power concept, such as the modelling of intermittent work capabilities, are exciting prospects for elite cycling. However, accurate calculation of the required parameters is traditionally time invasive and somewhat impractical. An alternative single test protocol (3-min All-out) has recently been proposed, but validation in an elite population is lacking. The traditional approach for parameter establishment, but with fewer tests, could also prove an acceptable compromise. **Methods:** Six senior Australian endurance track cycling representatives completed six efforts to exhaustion on two separate days over a three week period. These included 1, 4, 6, 8 and 10 minute self-paced efforts, plus the 3-min All-out protocol. Traditional work versus time calculations of CP and W’ using the five self-paced efforts were compared to calculations from the 3-min All-out protocol. The impact of using just two or three self-paced efforts for traditional CP and W’ estimation were also explored using thresholds of agreement (8W, 2.0kJ respectively). **Results:** CP estimated from the 3-min All-out approach was significantly higher than from the traditional approach (402±33W, 351±27W, $p<0.001$), whilst W’ was lower (15.5±3.0kJ, 24.3±4.0kJ, $p=0.02$). Five different combinations of two or three self-paced efforts led to CP estimates within the threshold of agreement, with only one combination deemed accurate for W’. **Conclusions:** In elite cyclists the 3-min All-out approach is not suitable to estimate CP when compared to the traditional method. However, reducing the number of tests used in the traditional method lessens testing burden whilst maintaining appropriate parameter accuracy.

Keywords: CP, W’, power-duration, maximal capacity, anaerobic capacity

INTRODUCTION

Based on the well-established relationship between exercise intensity and duration, the critical power model[1] has become a highly useful tool for training and competition analysis in the realms of high performance sport.[2]

The model describes the interaction of two parameters which together form an athlete's maximal work capacity. These include (1) a rate-limited parameter representing sustainable aerobic metabolism (critical power, CP), and (2) a capacity-limited parameter described by anaerobic energy contribution (W'). The mathematical modelling and subsequent interpretation of these two parameters has recently progressed, enabling coaches and sport scientists the ability to quantify an athlete's work capacity over both fixed and intermittent work pieces.[2-5]

High performance cycling presents an ideal avenue for the application of such modelling approaches due to the dynamic work rates seen in training and competition, as well as the capability to measure work rates through bicycle mounted power meters. However, the time invasive nature involved in acquiring the individualised model parameters (CP and W') has been a deterrent to its uptake, with traditional methods requiring four to five efforts to exhaustion over a range of durations.[6]

As a result, there have been a number of attempts to reduce the time burden of parameter establishment in cycling. For example using just two maximal efforts within the traditional method has been shown to accurately estimate CP and W', provided the duration of these efforts differ by at least five minutes (SEE of CP and W' were 1.7W and 0.88kJ, respectively).[7] Despite these findings, CP predictions using just two efforts are rarely used in research due to a perceived high risk of error.[6]

A single effort test has recently been proposed showing success at estimating CP and W' on par to the traditional five effort method (SEE 6W, 2.8kJ, respectively).[8-11] The single test involves a three minute maximal effort with an all-out pacing strategy (3-min All-out). Developed through deductive reasoning of the critical power model's mathematical framework, it is theorised that an all-out exercise strategy will completely deplete an individual's W' over the first minute or two of the test, hence forcing them to reduce their work rate to a level representing CP for the remaining duration. The CP is subsequently estimated as the average power over the final 30 seconds of the effort, while the W' is estimated as the work completed above this plateau power. Although the approach is viable within the mathematical constructs of the critical power model, it has been suggested that the protocol can often overestimate CP.[12-14] The cause of overestimation is commonly attributed to a failure in adopting a truly all-out pacing strategy during testing. This approach can result in W' continuing to contribute during the final 30 seconds of the work and hence being incorrectly attributed to CP. Whether this is a result of poor test execution, or highlights an implausible physiological assumption within this approach is unknown at this stage.

Despite practical appeal of a less time invasive method, neither the 3-min All-out approach[11] or using only two tests in the traditional approach[7] have been well explored in an elite population. This study provides an insight into the less time invasive methodologies and their appropriateness for CP and W' estimation in elite cyclists. Positive outcomes would reduce the time demands of parameter estimation and hence improve the utility of this bioenergetics model. Therefore, the aims of this study were to use international quality endurance cyclists to compare the:

(1) CP and W' estimates from the 3-min All-out strategy against the traditional five test approach, and

(2) CP and W' estimates of the traditional approach using two or three maximal effort tests as opposed to five.

METHODS

Subjects

Eight elite male endurance cyclists volunteered for this study, however only six completed the protocol (mean ±SD: age 20±1 yr; VO_{2max} 73±3 mL/kg/min; mass 73±1 kg). All athletes had won a senior international track endurance event for Australia in the past year, were highly competitive road cyclists at the pro-continental level, and were candidates for Olympic Games selection in 2016. All had consistent high performance training histories of at least four years and were familiar with maximal efforts of varying durations. The six athletes described were healthy and injury free throughout data collection. The protocol for this study was approved by the University of South Australia's Human Research Ethics Committee. Written, informed consent was provided by each athlete and permission was given by Cycling Australia for the use of the data.

Design

Data were collected during a national team camp under tightly controlled training and living routines. Testing was completed on two separate days within a three-week period. Each bout of testing was completed at the same time of day and preceded by a low-intensity road ride the day prior.

On the first day of testing athletes completed maximal ergometer cycling efforts over the durations of one, four and ten minutes. On the second testing day they completed the 3-min All-out test along with a six and eight minute maximal effort test. Each test was separated by 75 minutes to allow for adequate recovery[15] and preceded with a standardised competition-specific ramp warm up (Figure 1).

Methodology

Tests were completed using each cyclist's own road bicycles rear mounted to a Lemond Revolution trainer (Lemond, California, USA). This ergometer provides realistic sensations through the combined use of a heavy flywheel and fan-based wind resistance, whilst also allowing the athlete to change force requirements via standard gearing. Power output was measured at 2 Hz using Shimano 7800 SRM power meters (Schoberer Rad Me ß technik, Jülich, Germany). Each SRM had undergone a static calibration within the last three months.[16] Published data has shown that SRM power meters can have a measurement error of <1%,[17] and a coefficient of variation of 1.1%.[18] Zero-offsets were applied to each set of cranks between the warm up and test effort. A similar set up has been used to investigate the 3-min All-out test previously.[19]

Maximal Effort Tests

The aim of these tests, as described to the athletes, was to complete as much work as possible within the designated time frame. Athletes were instructed to start pedalling at approximately 50-60rpm, 15 seconds prior to the effort start. Cadence throughout the test was self-selected with athletes free to change gearing as they required. Athletes were given both verbal encouragement and occasional time updates to help ensure their exhaustion by the completion of the tests.

3-min All-out Test

The 3-min All-out test was performed as per the maximal effort protocol, however with the key instruction of ensuring an all-out pacing strategy was employed (that is, to go as hard as possible from the outset).

Data Analysis

Power meter data were downloaded using SRM software, exported, and then processed in Microsoft Excel. Each athlete's mean power for the five self-paced maximal efforts was converted to work (kJ) and plotted against time (seconds). As per the methodology of the linear work-time model, a linear regression line was fit to the data with the Y-intercept and slope of this line providing our traditional estimates of W' and CP, respectively.[20] This process was also completed using combinations of just two or three of the self-paced maximal effort trials to give numerous W' and CP estimates for each individual. The 3-min All-out test was analysed using previously published procedures whereby the mean power over the final 30 seconds was used to reflect the athlete's CP and work completed above CP was deemed to reflect W'.[11]

The parameter estimates of the traditional and the 3-min All-out test methodologies were compared using paired *t*-tests with significance set at 0.05.

Comparison between the traditional parameter estimates and those deduced from two or three tests were compared in relation to pre-set thresholds of agreement. Work output of elite athletes during repeated maximal efforts have a coefficient of variation of approximately 1%.[18,21] This variation was used to set thresholds by applying ±1% to the longest and shortest tests used in this study (one and ten minutes) and observing the resultant impact on CP and W' estimates. The effect on the CP and W' estimates for the sample population was 8W and 2.0 kJ, respectively. These errors were subsequently set as maximal tolerance levels.

RESULTS

A strong linear fit was found for the regression lines of each athlete's work versus time plots used in the traditional five test approach ($r>0.99$; $p<0.05$).

Both the CP and W' estimates for the 3-min All-out test were significantly different to the estimates from the traditional method ($p<0.01$ and $p=0.02$, respectively) (Tables 1 and 2). On average, the CP estimate was 51 W higher using the 3-min All-out test. W' averaged 8.8kJ lower using the 3-min All-out test compared to the traditional method.

Power output during the 3-min All-out tests showed a plateau after approximately 105s. An example 3-min All-out test is illustrated in Figure 2. This figure also shows the athlete's CP estimate using the traditional five test method, 3-min All-out test, and the athlete's ten minute average power as respective points of comparison.

In five of the six athletes the 3-min All-out CP estimate (402±33W) was higher than their average ten minute power (386±23W). The traditional measure of CP (351±27W) was below the maximum ten-minute average power for all subjects as would be expected.

The combination of the one, four and ten minute tests successfully estimated both CP and W' to within the thresholds of agreement of the traditional five test method (Figure 3). Four other combinations also predicted CP within the threshold, however, no other combination of trials was successful for predicting W'.

DISCUSSION

The critical power model has considerable potential applications within both elite cycling and in other high performance sports. However, to see this potential eventuate, the time demands of valid parameter estimation (CP and W') need to be reduced. This study has shown that the 3-min All-out test protocol previously proposed[11] is not an acceptable replacement for the traditional approach leading to substantial overestimation of CP and underestimation of W' in elite cyclists. However, reducing the number of tests used in the traditional method of CP and W' estimation seemed to be a more appropriate time-conscious progression for the present cohort of world-class cyclists.

3-Min All-out

Since initial publication there has been growing support for the 3-min All-out test as a valid alternative for obtaining parameters of the critical power model.[8-11] Using a mixture of active male and female participants, these studies have demonstrated both an agreement of the parameter estimates with the traditional method, as well as appropriate exercise sustainability of the CP workload derived. Our results, however, coincide with those showing overestimation of CP when using the 3-min All-out test.[12-14] These non-supportive studies also demonstrate their findings through both the direct comparison of parameter estimates,[14] as well as assessment of sustainability when exercising at CP.[12,13] Interestingly, the studies showing overestimation of CP involve only well trained or elite athletes, suggesting a subject group bias may be associated with these findings.

Explained within the context of the critical power model and the 3-min All-out test, overestimation of CP can occur when W' has not been fully depleted prior to, and is hence still contributing during, the final 30 seconds of the test. In other words, the overestimation of CP that occurred in our athletes suggests that either consciously or subconsciously, some form of pacing occurred. Considering the athletes in the present study were highly motivated, internationally competitive, and were instructed numerous times to adopt an all-out approach to the effort, this outcome was not expected. A comparison of the power profiles in this study, and those previously described during successful 3-min All-out tests [8] do not reveal any clear differences. Despite different outcomes both studies displayed plateau powers during the final two 30 second periods of the testing bout, hence suggesting that pacing errors leading to CP overestimation may not be easily identified.

Considering the prevalence of studies now showing CP overestimation using the 3-min All-out test protocol, it is worth discussing why this discrepancy is so common. The term teleoanticipation has been described as a subconscious fatigue avoidance mechanism that helps constrain an individual to a work rate which will allow successful completion of an exercise task.[22] Considering the 3-min All-out approach requires an athlete to fully deplete their W' prior to the end of the test, the opposing nature of these concepts seems clear. With teleoanticipation said to be based on past experiences,[23] as more experience of maximal work is gained, individuals should become better at maximising their work outputs over a given timespan. Most likely however, this would occur through learning appropriate workload distribution throughout the task, not so much the ability to take on an All-out pacing profile associated with a high risk of premature task failure (such as is required in the 3-min All-out test). This concept may explain the trend for more highly trained and experienced athletes to produce results that are not truly representative of CP or W'. Furthermore, considering this high level of maximal work awareness that experienced high performance athletes must possess, the fact that pacing is still prevalent in the 3-min All-out trials, despite high levels of motivation and encouragement to commit to an All-out strategy, perhaps alludes to the idea that such an approach is not actually possible. The assumption that one can maintain CP once W' is exhausted may be incorrect. This assumption is, after all, simply a mathematical derivative of the model, not a physiologically described trait.

3-Min All-out Ergometer Selection

Much of the research employing the 3-min All-out protocol has used an electromagnetically braked ergometer that allows a fixed resistance (i.e., torque) to be set. This approach means the athletes start with a very high cadence and corresponding high power, which progressively decreases as the athlete fatigues. The method employed in this current study, previously used by Francis,[19] involved an ergometer with the ability to vary resistance throughout the test, thus allowing for constantly self-selected cadence. Although impossible to fully discount the impact of this methodological difference to the studies outcome, others have shown this same result despite using the traditional electromagnetically braked ergometer. Furthermore, considering CP and W' should collectively describe maximal work capacity, and suboptimal cadences have been shown to result in a decreased total work output,[24,25] it seems highly inappropriate to use a test protocol spaning such an extreme cadence range. A method which allows for constantly self-selected cadence hence appears to be better aligned with the theme of exploring maximal work capacity.

Reducing No. of Tests in the Traditional CP Method

Also explored in this study, was the impact of reducing the number of tests used in the traditional method of CP and W' estimation. Reducing the number of tests yielded mixed results in determining parameter estimates, however was largely controlled by the duration of the tests included. Keeping the span of the tests fixed and broad tended to maintain parameter accuracy. Using a narrow range of tests or only two tests was associated with less accuracy and is not recommended for elite athletes. The most successful combination found was a three-test protocol including the one, four and ten minute durations. These tests can be achieved on a single testing day with high-performance athletes and provides reliable estimates of the critical power model parameters. The results of this study are slightly more conservative than those previously published who suggested just two maximal efforts were adequate for parameter estimation.[7]

PRACTICAL APPLICATIONS

Although the sample size of this study may be considered small, the elite nature of the participants mean that it is difficult to increase participant numbers without deviating from the population of interest, that is male high performance endurance cyclists.

To those working with this population the authors recommend that severe caution is taken with regards to parameters calculated from the 3-Min All-out test.

The traditional CP linear-work model however, can be used with three carefully selected maximal efforts, completed within a three hour window, and yields parameter outputs which practitioners can be confident in using.

When selecting efforts, the authors would recommend targeting durations covering a relatively wide span of pre-existing guidelines (1-10mins)[6] (2-20mins)[2], whilst maintaining relatively fixed selections for repeat testing.

Finally, the authors stress the necessity of including only truly maximal efforts when calculating output parameters. Although including extra efforts in the model is often commended in this area of research, practitioners should be critical of the impact that an increased testing burden has on levels of subject motivation.

Should researchers or practitioners still wish to investigate the 3-min All-out test, future research should focus on testing the assumption that CP can be maintained when W' has been fully depleted.

CONCLUSION

The 3-min All-out test significantly overestimated CP and underestimated W' in elite cyclists and hence is not recommend to be used as a replacement for the traditional method. Utilising the traditional linear work-time method with three carefully selected maximal performances seems to be a reliable and time-efficient alternative, and is currently the best practice for use in high performance athletes.

ACKNOWLEDGEMENTS

The authors would like to acknowledge and thank Cycling Australia, the athletes, and the head men's endurance coach for their efforts and contributions towards this research.

REFERENCES

1. Monod H, Scherrer J. The work capacity of a synergistic muscular group. *Ergonomics.* 1965;8(3):329-338.

2. Vanhatalo A, Jones AM, Burnley M. Application of critical power in sport. *International Journal of Sports Physiology & Performance.* 2011;6(1):128-136.

3. Skiba PF, Chidnok W, Vanhatalo A, Jones AM. Modeling the expenditure and reconstitution of work capacity above critical power. *Medicine and Science in Sports and Exercise.* 2012;44(8):1526-1532.

4. Morton R, Billat L. The critical power model for intermittent exercise. *European Journal of Applied Physiology.* 2004;91(2):303-307.

5. Skiba PF, Clarke D, Vanhatalo A, Jones AM. Validation of a novel intermittent w'model for cycling using field data. *International Journal of Sports Physiology & Performance.* 2014;9(6).

6. Hill DW. The critical power concept. A review. *Sports Medicine.* 1993;16(4):237-254.

7. Housh DJ, Housh TJ, Bauge SM. A methodological consideration for the determination of critical power and anaerobic work capacity. *Research Quarterly for Exercise and Sport.* 1990;61(4):406-409.

8. Burnley M, Doust JH, Vanhatalo A. A 3-min all-out test to determine peak oxygen uptake and the maximal steady state. *Medicine and science in sports and exercise.* 2006;38(11):1995-2003.

9. Dekerle J, Vanhatalo A, Burnley M. Determination of critical power from a single test. *Science & Sports.* 2008;23(5):231-238.

10. Simpson L, Jones A, Skiba P, Vanhatalo A, Wilkerson D. Influence of Hypoxia on the Power-duration Relationship during High-intensity Exercise. *International journal of sports medicine.* 2015;36(2):113-119.

11. Vanhatalo A, Doust J, Burnley M. Determination of critical power using a 3-min all-out cycling test. Lippincott Williams & Wilkins; 2007.

12. Bergstrom HC, Housh TJ, Zuniga JM, et al. Mechanomyographic and metabolic responses during continuous cycle ergometry at critical power from the 3-min all-out test. *Journal of Electromyography and Kinesiology.* 2013;23(2):349-355.

13. McClave SA, LeBlanc M, Hawkins SA. Sustainability of critical power determined by a 3-minute all-out test in elite cyclists. *The Journal of Strength & Conditioning Research.* 2011;25(11):3093-3098.

14. Karsten B, Jobson SA, Hopker J, Passfield L, Beedie C. The 3-min test does not provide a valid measure of critical power using the SRM isokinetic mode. *Int J Sports Med.* 2014;35:304-309.

15. Galbraith A, Hopker J, Lelliott S, Diddams L, Passfield L. A single-visit field test of critical speed. *International Journal of Sports Physiology & Performance.* 2014;9(6).

16. Wooles AL, Robinson AJ, Keen PS. A static method for obtaining a calibration factor for SRM bicycle power cranks. *Sports Engineering.* 2005;8(3):137-144.

17. Abbiss C, Quod M, Levin G, Martin D, Laursen P. Accuracy of the Velotron ergometer and SRM power meter. *International journal of sports medicine.* 2009;30(2):107.

18. Paton C, Hopkins W. Ergometer error and biological variation in power output in a performance test with three cycle ergometers. *International journal of sports medicine.* 2006;27(6):444-447.

19. Francis Jr JT, Quinn TJ, Amann M, LaRoche DP. Defining intensity domains from the end power of a 3-min all-out cycling test. *Medicine and science in sports and exercise.* 2010;42(9):1769-1775.

20. Jones AM, Wilkerson DP, DiMenna F, Fulford J, Poole DC. Muscle metabolic responses to exercise above and below the "critical power" assessed using P-MRS. *American journal of physiology - regulatory, integrative and comparative physiology.* 2008;294(2):585-593.

21. Lamberts RP, Swart J, Woolrich RW, Noakes TD, Lambert MI. Measurement error associated with performance testing in well-trained cyclists; application to the precision of monitoring changes in training status. *International SportMed Journal.* 2009;10(1):33-44.

22. Faria IE. Energy expenditure, aerodynamics and medical problems in cycling, an update. *Sports Medicine.* 1992;14(1):43-63.

23. Mauger A, Jones A, Williams C. Influence of feedback and prior experience on pacing during a 4-km cycle time trial. *Medicine+ Science in Sports+ Exercise.* 2009;41(2):451.

24. Woolford MS, Withers TR, Craig PN, Bourdon CP, Stanef T, McKenzie I. Effect of pedal cadence on the accumulated oxygen deficit, maximal aerobic power and blood lactate transition thresholds of high-performance junior endurance cyclists. *European Journal of Applied Physiology and Occupational Physiology.* 1999;80(4):285-291.

25. Barker T, Poole DC, Noble ML, Barstow TJ. Human critical power–oxygen uptake relationship at different pedalling frequencies. *Experimental physiology.* 2006;91(3):621-632.

“Predicting Critical Power in Elite Cyclists: Questioning Validity of the 3-min All-out Test”
by Bartram JC, Thewlis D, Martin DT, Norton KI
International Journal of Sports Physiology and Performance

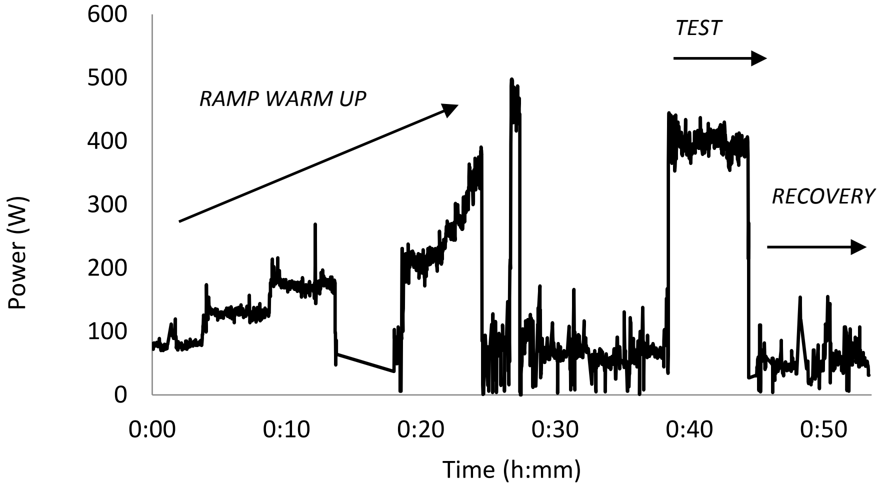

FIGURE 1 - An example of the warm up and testing protocol for each test. There was approximately 30 minutes of recovery time from the end of the test to the beginning of the next warm up or 75 minutes until the next test commenced.

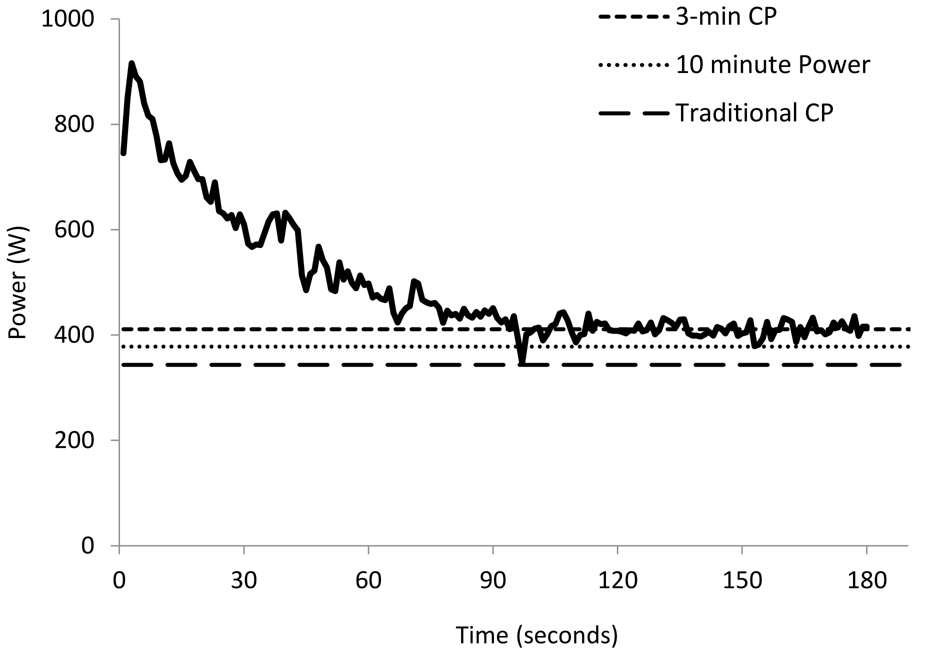

FIGURE 2 - Example power profile of an athlete's 3-min All-out test (solid line), along with their 3-min All-out test CP (medium dashes), their traditionally calculated CP (big dashes), and the athlete's ten minute test power as a reference to sustainable power output (dots)

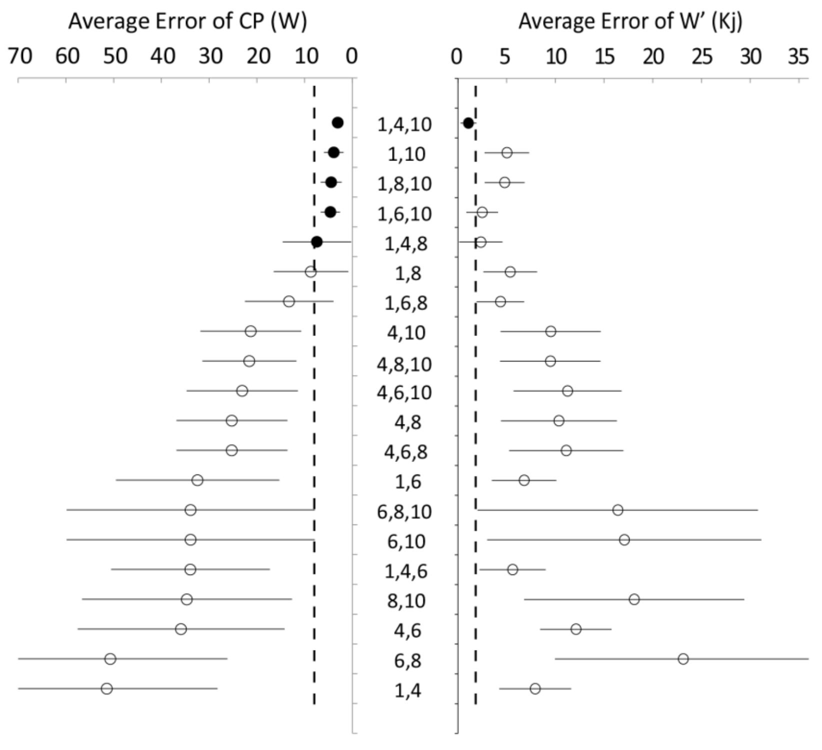

FIGURE 3 - Summary of the average error of CP (left side) and W' (right side) estimates using various test combinations (test durations are shown down the centre) versus the traditional five test estimate. The thresholds of agreement are represented by the vertical dashed lines and sit at 8.0W and 2.0kJ, respectively. Mean values which sit within the threshold are identified by the filled markers. Error bars show the standard deviation of the errors.

"Predicting Critical Power in Elite Cyclists: Questioning Validity of the 3-min All-out Test"
by Bartram JC, Thewlis D, Martin DT, Norton KI
International Journal of Sports Physiology and Performance

Table 1. A comparison of the CP estimates (W) for the traditional five test approach versus the 3-min All-out test. *p<0.001 95% CI (30 to 72)

Subject	Traditional CP (W)	3-min All-out CP (W)	Difference (W)
1	324	375	51
2	371	380	8
3	357	418	61
4	343	411	68
5	313	365	51
6	395	464	69
Mean	351	402	51*
SD	27	33	20

Table 2. A comparison of the W' estimates (kJ) for the traditional five effort approach versus the 3-min All-out test. *p= 0.02 95% CI (-2.6 to -15)

Subject	Traditional W' (kJ)	3-min All-out W'(kJ)	Difference (kJ)
1	25.8	12.4	-13.4
2	21.8	12.9	-8.9
3	25.9	15.0	-10.9
4	20.9	15.4	-5.5
5	31.6	15.4	-16.1
6	19.7	21.7	20.2
mean	24.3	15.5	-8.8*
SD	4.0	3.0	5.9