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Critical Power: Several Basic Points

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Abstract

This article briefly reviewed several basic points about the 2-parameter and 3-parameter critical power models and some standard testing methods currently used for critical power estimation. Moreover, the last section of this article provides a brief overview of the process of W' balance model development and its current applications.

Keywords

A Critical power model; Critical power estimation; W' balance model; SK1 and SK2 models.

1. INTRODUCTION

Since the first description of the hyperbolic relationship between race speed and time in running and swimming by Archibald Hill [1], almost a hundred years have passed. Of note, the concept of 'critical power' (CP) was first presented by Monod and Scherrer in 1965 through a series of measurements of work- time to exhaustion for groups of muscles [2]. In1981, Moritani and his colleagues extended the CP concept to be applied in whole-body ergometer cycling [3]. Since then, CP has been studied considerably in many sports areas and some newer derivative concepts have also emerged, such as critical load [4] and W'balance models [5, 6].

Despite the CP model thriving today, it faces many problems [7] and doubts abound [8, 9]. This article was briefly to review and summarize some essential points about the CP model.

2. LITERATURE REVIEW

2.1. The critical power (CP) model

Popularly, CP is a decent amount of power output that a subject can maintain for a considerable time when exercising. Studies reported that people could exercise for roughly 30 minutes on average at CP intensity in the opening time test; However, there was a vast individual difference [10, 11]. Other studies reported that all participants could complete at least 24 minutes of cycling exercises at CP intensity without duress in a time-fixed test [12, 13].

There are the two-parameter (2-p) CP model (Figure 1) and the three-parameter (3-p) CP model [14] (Figure 2) based on the parameter number categorisation of CP models. The 2-p CP model is straightforward and it can be expressed by Equation (Eq.) 1, 2, 3 [2, 15]. The two parameters refer to CP and W'.

$$T_{lim} = W' / (CP - P) \quad (1)$$

$$P = W' / T_{lim} + CP \quad (2)$$

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$$P = CP \cdot T_{lim} + W' \quad (3)$$

The parameters in Equations 1,2, and 3 represent the same: P is the power output,

T_{lim} is the time to exhaustion under power output P, W' is the energy reserve, and CP is the critical power.

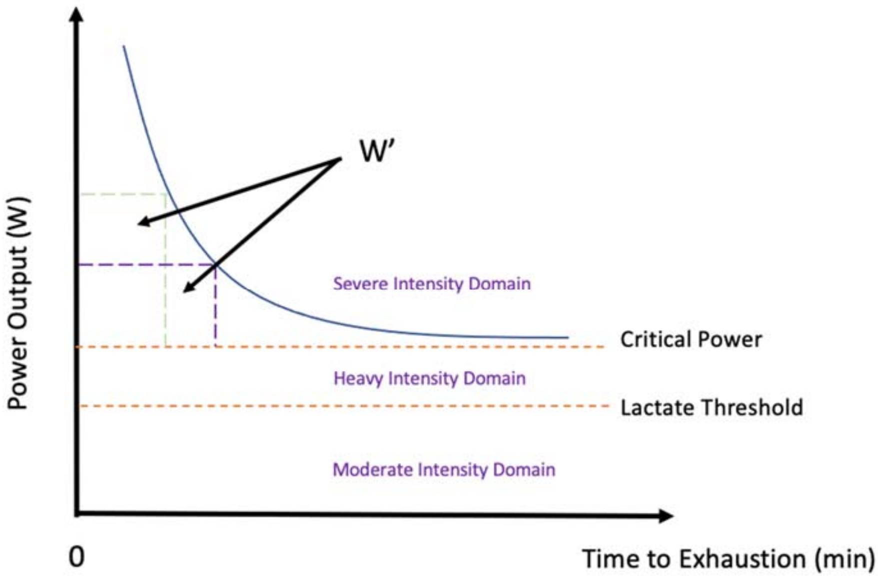

Figure 1. The 2-parameter critical power model

The 3-p model (Eq.5) allowed the existence of a negative time asymptote k (Eq.4) based on the 2-p model. And the third parameter refers to maximal instantaneous power (P_{max}) when time equals zero [14]. Morton's original intention was to make improvements for the 2-p CP model, as Morton assumed there should be a P_{max} at T_{lim} = 0 and it was proportional to W' instantly [14]. Moreover, another remark for the 2-p model is that the time asymptote is zero, thus, theoretically, the time can be infinitely close to zero but cannot be zero, which gives a plausible expression that when the time is infinitely close to zero, the power output can be infinitely large. Undoubtedly, this explanation is physiologically untenable.

$$k = W'/(CP - P_{max}) \quad (4)$$

$$T_{lim} = W'/(P - CP) + W'/(CP - P_{max}) \quad (5)$$

that is, when $T_{lim} = 0$, $P = P_{max}$.

Studies reported that the accuracy of the 3-p model is promising [16, 17], especially since the 3-p model is a better descriptor when high power output and short exhaustion time (T_{lim} < 2 minutes) trials were involved [18, 19]. However, the 2-p model is still the most used model, as it requires as less as two time to exhaustion (TTE) trials for plotting a CP model. In contrast to the 2-p model, the 3-p model requires at least three TTE trials as it has three unknown parameters (Eq.5). However, usually more trials (>3 trials) were taken for premises of accuracy [16, 20], which makes the testing procedure complex and demanding.

Furthermore, the extreme exercise intensity represented by P_{max} is not much compatible with the CP model's original intention to study 'exercise without fatigue,' which may be another reason why the 3P model is less commonly used (Figure 2).

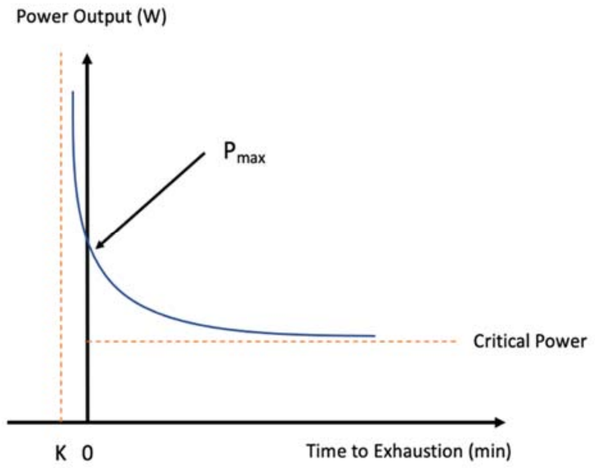

Figure 2. A comparison between the 3-p CP model (left) and the 2-p CP model (right).

2.2. Testing methods for CP

Since the first experiment that proposed the concept of CP [2], it was inseparable from time to exhaustion. All kinds of CP test methods [21, 22] are exhaustive tests. In general, there are five types of CP test methods: the constant work test, the constant time test, the three minutes all-out test (3AOT), the ramp all-out test (RAOT), and the last one is to extract data from maximal power from daily training and races to fit an individual CP model. Cycling is often the exercise selected for measuring power output and time to exhaustion. Ergometers with electromagnetic brakes are usually the implements.

The constant work tests

The constant work test (Figure 3) is known as the time-to-exhaustion trial (TTE). It has an extra ramp incremental test for determining the peak power output (P_{peak}) before the subsequent TTE trials [18, 23]. Subjects are required to exercise at several predetermined constant-work rates (CWR) derived from the peak power output to exhaustion; various power outputs (P) and times to exhaustion (T_{lim}) obtained in the series of trial can be plotted into the CP model. Usually, it is recommended choose CWR that could elicit exhaustion between 2-15 minutes [24, 25]. The power output corresponding to this time interval is about around 120%-85% P_{peak} [18]. Of note, the percentage of P_{peak} given above is just a rough reference based on the published data. Actual conditions may vary from person to person. Typically, 24 - 72 hours of recovery between each TTE trial is required [19, 21].

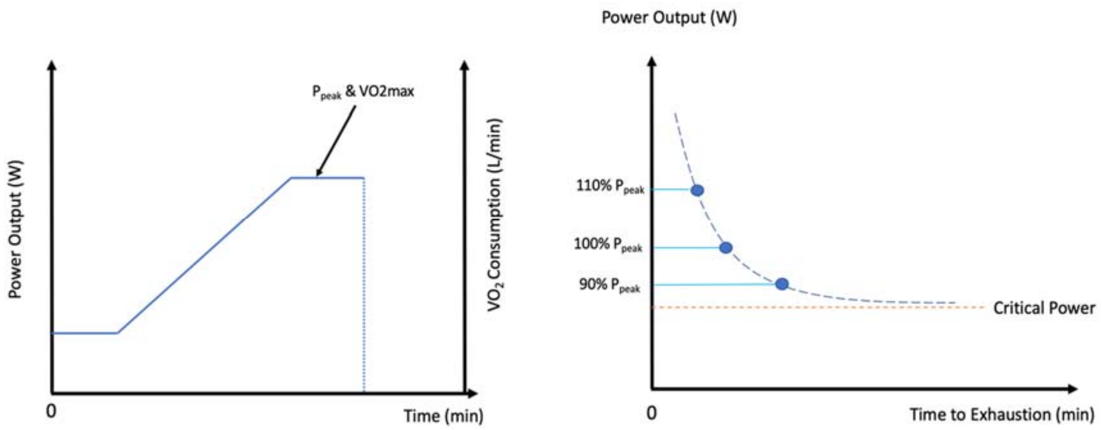

Figure 3. The ramp incremental test (left) and the constant work test at predetermined rates (right).

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The constant time tests

The constant time test (Figure 4) is also known as time trials (TTs), which is similar to the TTE trials, but it does not require any ramp incremental test in advance. Therefore, it is more commonly used in current practice than TTE trials. Another advantage of TTs is that it is a self-pacing test, and a study reported self-pacing rhythm could improve athletic performance [26]. The participant should undergo at least two exhaustive trials with full power output within the prescribed time limit to exhaustion (usually ranging from 2 -15 minutes) for an accurate estimation of CP and W'[27, 28].

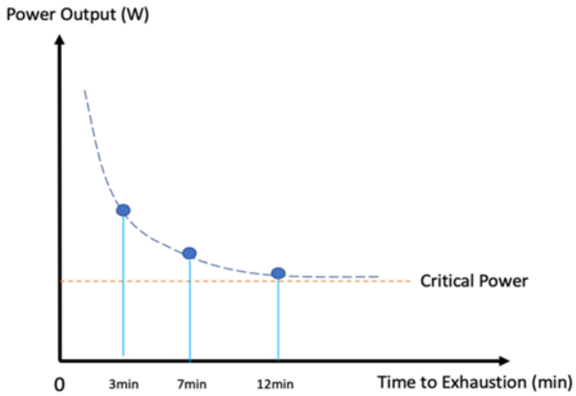

Figure 4. The constant time test at predetermined time

Three or more exhaustive trials are required to estimate CP accurately for participants unfamiliar with the test. Nonetheless, those repetitive demanding tests are disadvantageous for the application and research of CP, especially for asking untrained participants to push to their physiological limit multiple times.

The three minutes all-out tests

The 3AOT [29] method was developed to lessen the burden for the test takers through CP estimation process, as the CP and W' can be estimated by only one maximal effort test. The subject is required to put full power in the three minutes of cycling. The theoretical basis for this test is that it assumes a relative long duration, un-paced full power output cycling will completely deplete the subject's W' in the first 2.5 minutes of the test; As the power output continues to decrease and W' is fully depleted, the subject could only maintain the exercise power output at CP in the last 30 seconds of the test (Figure 5). Therefore, the CP is determined by the average power output at the last 30s of the test, and W' is referred to by the total work done above CP through the test [30].

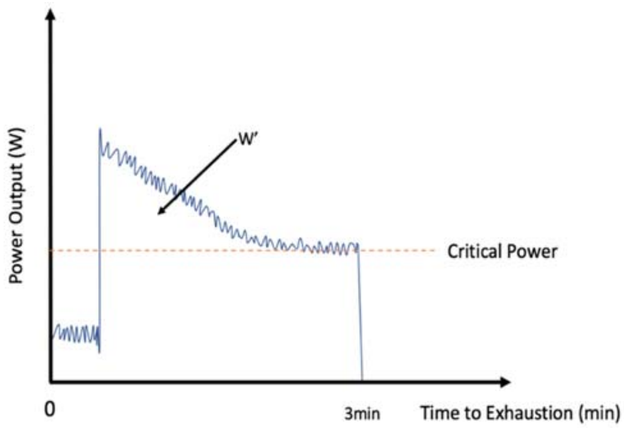

Figure 5. The three minutes all-out test.

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However, because of the accuracy limitations, the CP was usually overestimated [31, 32], and the W' was reported to be underestimated [33]. 3AOT is used quite limitedly in scientific research compared to practice [22].

The ramp all-out test

The ramp all-out test (RAOT) (Figure 6) is another invented method for estimating CP to reduce the burden of repeated trials based on the 3AOT method [34]. Simply put, RAOT is a ramp incremental test immediately following a three-minute maximal efforts sprint. A ramp incremental test is taken for depleting the W' completely. After completing the ramp incremental test, CP could be determined by the power output plateau of the last three-minute maximal efforts sprint, and W' is determined by the total work done above CP [22, 34]. An advantage of RAOT is that CP can be determined through one lab visit, and preliminary tests are not required. Due to the ramp incremental test was undertaken, more information could be obtained at once, such as gas exchange threshold (GET) and VO_{2max}. The most importantly, the ramp incremental test is a much more reliable "exercise" for completely depleting W' compared to the first 2.5 minutes of 3AOT, as 3AOT test is not always a valid test due to many factors, such as power prematurely drop below the end power which led to W' reconstitution during the first 2.5 minutes of the test, or power output failed to plateau at the last 30 seconds [35].

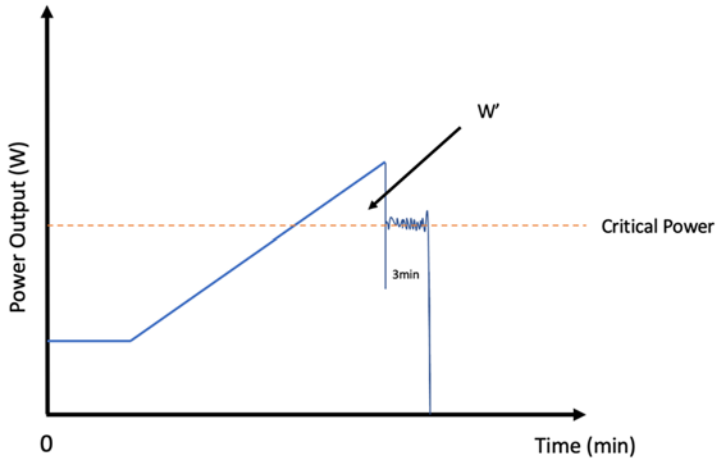

Figure 6. The ramp all-out test.

The past racing data

A widespread concern for all four tests mentioned above is that a subject could underperform during the tests for various reasons, but he/she is not possible to overperform beyond the ability. Thus, there is always a risk of underestimating CP or W'[22]. Using past training and racing data could ease this issue to a certain extent (Figure 7), as the data comes from multiple events over a relatively long period, which makes the estimation of CP and W' more confident. Still, the time to exhaustion range should be 2 – 15 minutes.

One unresolved issue about using past data for determining CP and W' is that there are no clear guidelines for the validity period of collecting data. As the physiological state of an athlete changes significantly among different training phases, it remains unclear how long is considered a reasonable period that the data can be collected and involved in CP estimations.

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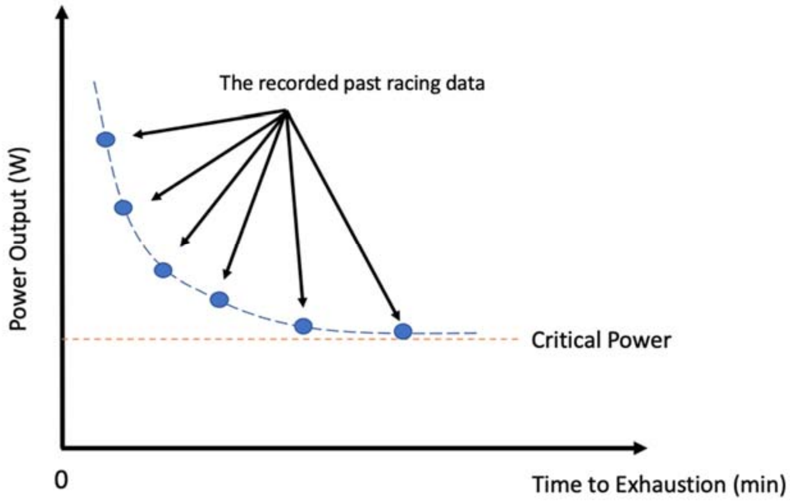

Figure 7. Estimation of CP based on the past racing data.

2.3. The W' balance model and its prospects.

The first two articles that proposed critical power [2] and critical speed (CS)[36], respectively, realised the existence of energy reconstitution; However, this understanding of the energy reconstitution was not reflected in their proposed linear equation. Therefore, strictly speaking, the 2-parameter CP model can only be applied when subjects exercise at an intensity greater than or equal to their CP at any given moment. Otherwise, uncalculated energy reconstitution will affect the accuracy of the CP model (we assume that there is a negligible amount of energy reconstitution when exercising above CP). Other scholars had the same view [37].

Since the turn of the millennium, various W' balance models have been proposed for intermittent exercise. In 2004, Morton and Billat first raised a new model (Eq.6) for intermittent exercises [38].

$$T = n(T_w + T_r) + \frac{W' - n[(P_w - CP)T_w - (CP - P_r)T_r]}{P_w - CP} \tag{6}$$

Eq.6 was very ground-breaking as it tried to calculate the total endurance time for an intermittent exercise with various power outputs and time segments of varying lengths. In Eq.6, T refers to the total endurance time. n is the total number of work-rest cycles. T_w and T_r are durations for work and rest, respectively. P_w and P_r are power outputs for work and rest, respectively. Please note that at any 'rest' interval, P_r does not necessarily to be zero but must be less than CP. Moreover, the mean power output for the whole exercise should greater than CP. This is the prerequisite for W' reconstitution, which can be expressed as Eq.7 [38].

$$(P_w T_w + P_r T_r) / (T_w + T_r) > CP \tag{7}$$

The work of Morton and Billat was highly innovative. They substituted the measured n, T_w, T_r, P_w, and P_r into Equation 6 to estimate the CP and W' for intermittent exercises was strange, as this behaviour did not compatible with the definition of CP. Because it seemed they were trying to estimate multiple new CP and W' based on each intermittent exercise, this is burdensome compared to calculating the T_{lim} for each intermittent exercise and not logical.

Nonetheless, the biggest problem of the model developed by Morton and Billat was that they believed that W' recovery could be expressed linearly as (CP - P_r) T_r in Eq.6. This misconception

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was understandable at the time. However, it was proved that W' recovery was curvilinear, and it was influenced by recovery durations and intensity [6, 39, 40], while the kinetics of W' reconstitution was not entirely clear.

In 2012, Skiba and his colleagues first raised an integral formed W' balance model (W'$_{BAL-INT}$)[5], which also refers as the SK1 model (Eq.8 & 9).

$$W'_{bal} = W'_0 - \int_0^t (W'_{exp})(e^{-(t-u)/\tau_{w'}}) \times du \tag{8}$$

$$\tau_{w'} = 546e^{(-0.01D_{cp})} + 316 \tag{9}$$

In Eq.8 & 9, W'_{bal} refers to the remaining W' at time t, W'_0 is the subject's initial W', W'_{exp} is the expanded W', t-u is the recovery durations, $\tau_{w'}$ is the constant of W' reconstitution from total depletion, D_{cp} is the difference between CP and power output.

The SK1 model has serval limitations. The first was that in Eq.8, both sides' units were unequal. On the left side of the equation is Joule, and the right side is Joule – Joule x Seconds [41]. Furthermore, the difficulties in calculating the instantaneously varied D_{cp}, and the doubted numeric coefficients in Eq.9 made the model difficult in practical applications. Furthermore, Skiba's team has reservations about the SK1 model's reliability for sports applications outside of cycling [6]. Overall, the SK1 model performed mediocrely reported in other validation studies and it did not meet expectations [42, 43].

In 2015, Skiba and his team came up with an ordinary differential equation W' balance model(W'$_{BAL-ODE}$) [6], which also refers as the SK2 model (Eq.10).

$$W'_{bal} = W'_0 - W'_{exp} e^{-D_{cp}t/W'_0} \tag{10}$$

In Eq.10, W'_{bal} refers to the W'balance at time t, W'_0 is the initial W' of the subject, W'_{exp} is the expanded W' prior time t, and D_{cp} is the difference between power output and CP.

A very noticeable change was that $\tau_{w'}$ in Eq.8 & 9 was replaced by W'_0/D_{cp}, which simplified the process of calculating W'balance, as $\tau_{w'}$ was reported to highly variable among individuals [5, 6].

At present, the more commonly used model is the SK2 model, but in general, all current W'$_{BAL}$ models are still immature in practical use [42-47].

Despite the many limitations of the current W' balance models, with extreme model development difficulties, its prospects are undeniable as W' balance models greatly expand the range of applications. Skiba had a very positive outlook on the future of W' balance models in 2012 as he believed that the W' balance models could be cooperated in specific wearable devices to give athletes real-time feedback on recharging or discharging W' during training or competitions in the future [48].

3. SUMMARISATION

At present, the 2-p CP model is still a commonly used model across practice and research. However, the 3-p CP model is more reliable for CP and W' estimation when short-period (<2 minutes), high-intensity trials get involved. As for the testing methods for CP, each method has its pros and cons, and it should be selected carefully based on the context. The prospects of W' balance models are promising. It has attracted much attention from researchers. However, it is

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still in the development stage, and there is probably quite some time before it is applied in practice.

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REFERENCES

[1] Hill, A.V., The physiological basis of athletic records. The Scientific Monthly, 1925. 21(4): p. 409-428.

[2] Monod, H. and J. Scherrer, The work capacity of a synergic muscular group. Ergonomics, 1965. 8(3): p. 329-338.

[3] Moritani, T., et al., Critical power as a measure of physical work capacity and anaerobic threshold. Ergonomics, 1981. 24(5): p. 339-350.

[4] Dinyer, T.K., et al., Linear and Nonlinear Modeling of Critical Load. Journal of Exercise Physiology Online, 2020. 23(5).

[5] Skiba, P.F., et al., Modeling the expenditure and reconstitution of work capacity above critical power. Medicine and science in sports and exercise, 2012. 44(8): p. 1526-1532.

[6] Skiba, P.F., et al., Intramuscular determinants of the ability to recover work capacity above critical power. European journal of applied physiology, 2015. 115(4): p. 703-713.

[7] Dotan, R., A critical review of critical power. Eur J Appl Physiol, 2022. 122(7): p. 1559-1588.

[8] Gorostiaga, E.M., L. Sanchez-Medina, and I. Garcia-Tabar, Over 55 years of critical power: Fact or artifact? Scand J Med Sci Sports, 2022. 32(1): p. 116-124.

[9] Winter, E.M., "Critical power": time to abandon. Med Sci Sports Exerc, 2011. 43(3): p. 552; author reply 553.

[10] Brickley, G., J. Doust, and C. Williams, Physiological responses during exercise to exhaustion at critical power. European journal of applied physiology, 2002. 88(1): p. 146-151.

[11] Housh, D.J., T.J. Housh, and S.M. Bauge, The accuracy of the critical power test for predicting time to exhaustion during cycle ergometry. Ergonomics, 1989. 32(8): p. 997-1004.

[12] Overend, T.J., et al., Physiological responses of young and elderly men to prolonged exercise at critical power. Eur J Appl Physiol Occup Physiol, 1992. 64(2): p. 187-93.

[13] Poole, D.C., et al., Metabolic and respiratory profile of the upper limit for prolonged exercise in man. Ergonomics, 1988. 31(9): p. 1265-79.

[14] Hugh Morton, R., A 3-parameter critical power model. Ergonomics, 1996. 39(4): p. 611-619.

[15] Vanhatalo, A., A.M. Jones, and M. Burnley, Application of critical power in sport. International journal of sports physiology and performance, 2011. 6(1): p. 128-136.

[16] Gaesser, G.A., et al., Estimation of critical power with nonlinear and linear models. Med Sci Sports Exerc, 1995. 27(10): p. 1430-8.

[17] Bergstrom, H.C., et al., Differences among estimates of critical power and anaerobic work capacity derived from five mathematical models and the three-minute all-out test. J Strength Cond Res, 2014. 28(3): p. 592-600.

[18] Vinetti, G., et al., Experimental validation of the 3-parameter critical power model in cycling. Eur J Appl Physiol, 2019. 119(4): p. 941-949.

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202301_9(1).0007

[19] Mattioni Maturana, F., et al., Critical power: How different protocols and models affect its determination. J Sci Med Sport, 2018. 21(7): p. 742-747.

[20] Bull, A.J., et al., Effect of mathematical modeling on the estimation of critical power. Med Sci Sports Exerc, 2000. 32(2): p. 526-30.

[21] Puchowicz, M.J., et al., The critical power model as a potential tool for anti-doping. Frontiers in physiology, 2018. 9: p. 643.

[22] Chorley, A. and K.L. Lamb, The Application of Critical Power, the Work Capacity above Critical Power (W'), and its Reconstitution: A Narrative Review of Current Evidence and Implications for Cycling Training Prescription. Sports (Basel), 2020. 8(9).

[23] Adami, A., et al., Effects of step duration in incremental ramp protocols on peak power and maximal oxygen consumption. Eur J Appl Physiol, 2013. 113(10): p. 2647-53.

[24] Poole, D.C., et al., Critical power: an important fatigue threshold in exercise physiology. Medicine and science in sports and exercise, 2016. 48(11): p. 2320.

[25] Muniz-Pumares, D., et al., Methodological Approaches and Related Challenges Associated With the Determination of Critical Power and Curvature Constant. J Strength Cond Res, 2019. 33(2): p. 584-596.

[26] Black, M.I., et al., Self-pacing increases critical power and improves performance during severe-intensity exercise. Applied physiology, nutrition, and metabolism, 2015. 40(7): p. 662-670.

[27] Simpson, L.P. and M. Kordi, Comparison of Critical Power and W′ Derived From 2 or 3 Maximal Tests. International Journal of Sports Physiology and Performance, 2017. 12(6): p. 825-830.

[28] Housh, D.J., T.J. Housh, and S.M. Bauge, A methodological consideration for the determination of critical power and anaerobic work capacity. Res Q Exerc Sport, 1990. 61(4): p. 406-9.

[29] Vanhatalo, A., J.H. Doust, and M. Burnley, Determination of critical power using a 3-min all-out cycling test. Medicine and science in sports and exercise, 2007. 39(3): p. 548-555.

[30] Burnley, M., J.H. Doust, and A. Vanhatalo, A 3-min all-out test to determine peak oxygen uptake and the maximal steady state. Med Sci Sports Exerc, 2006. 38(11): p. 1995-2003.

[31] McClave, S.A., M. LeBlanc, and S.A. Hawkins, Sustainability of critical power determined by a 3-minute all-out test in elite cyclists. J Strength Cond Res, 2011. 25(11): p. 3093-8.

[32] Bergstrom, H.C., et al., Metabolic and neuromuscular responses at critical power from the 3-min all-out test. Appl Physiol Nutr Metab, 2013. 38(1): p. 7-13.

[33] Bartram, J.C., et al., Predicting Critical Power in Elite Cyclists: Questioning the Validity of the 3-Minute All-Out Test. Int J Sports Physiol Perform, 2017. 12(6): p. 783-787.

[34] Murgatroyd, S.R., et al., 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(9): p. 1863-74.

[35] Clark, I.E., S.R. Murray, and R.W. Pettitt, Alternative procedures for the three-minute all-out exercise test. J Strength Cond Res, 2013. 27(8): p. 2104-12.

[36] Ettema, J., Limits of human performance and energy-production. Internationale Zeitschrift für Angewandte Physiologie Einschließlich Arbeitsphysiologie, 1966. 22(1): p. 45-54.

[37] Marwood, S. and R.P. Goulding, Over 55 years of critical power: Fact. Scand J Med Sci Sports, 2022. 32(6): p. 1064-1065.

[38] Morton, R.H. and L.V. Billat, The critical power model for intermittent exercise. European journal of applied physiology, 2004. 91(2): p. 303-307.

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202301_9(1).0007

[39] Ferguson, C., et al., Effect of recovery duration from prior exhaustive exercise on the parameters of the power-duration relationship. Journal of applied physiology, 2010. 108(4): p. 866-874.

[40] Chidnok, W., et al., Exercise tolerance in intermittent cycling: application of the critical power concept. Med Sci Sports Exerc, 2012. 44(5): p. 966-76.

[41] Sreedhara, V.S.M., G.M. Mocko, and R.E. Hutchison, A survey of mathematical models of human performance using power and energy. Sports Medicine - Open, 2019. 5(1): p. 54.

[42] Caen, K., et al., The Reconstitution of W' Depends on Both Work and Recovery Characteristics. Med Sci Sports Exerc, 2019. 51(8): p. 1745-1751.

[43] Chorley, A., et al., Slowing the Reconstitution of W' in Recovery With Repeated Bouts of Maximal Exercise. Int J Sports Physiol Perform, 2019. 14(2): p. 149-155.

[44] Bartram, J.C., et al., Accuracy of W' Recovery Kinetics in High Performance Cyclists-Modeling Intermittent Work Capacity. Int J Sports Physiol Perform, 2018. 13(6): p. 724-728.

[45] Bartram, J.C., et al., Validating an Adjustment to the Intermittent Critical Power Model for Elite Cyclists—Modeling W′ Balance During World Cup Team Pursuit Performances. International Journal of Sports Physiology and Performance, 2022. 17(2): p. 170-175.

[46] Sreedhara, V.S.M., et al., Modeling the Recovery of W' in the Moderate to Heavy Exercise Intensity Domain. Med Sci Sports Exerc, 2020. 52(12): p. 2646-2654.

[47] Skiba, P.F. and D.C. Clarke, The W′ Balance Model: Mathematical and Methodological Considerations. International Journal of Sports Physiology and Performance, 2021. 16(11): p. 1561-1572.

[48] Skiba, P.F., The kinetics of the work capacity above critical power. University of Exeter, 2014.