



Running work capacity over critical power: a variable rather than a constant parameter

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Abstract

The work capacity over critical power is theoretically defined by the curvature constant. However, this parameter has been characterized by a large standard error of the estimate. Therefore, this study aims to determine the validity of this parameter to represent the work performed over critical power on different time trials along the severe intensity domain. Athletes performed four-time trials (3, 5, 10 and 20 min) in a two-week training period on a 400-meter outdoor track. The mean power output of each time trial was measured through the Stryd power meter, and the inverse of the time model was used. The work depletion was modelled in each time trial until exhaustion. The standard error of the estimate was 2.4 (1.0) % for critical power and 12.3 (4.3) % for work over it. Although no significant differences were reported between the work estimated by the critical power model and the one performed on each time trial ($P \geq 0.058$), the 95% confidence intervals revealed potential significant discrepancies at the 10-min (-1.4 [-3.1 to 0.3] kJ) and 20-min (2.2 [-0.1 to 4.6] kJ) time trials, respectively. If the work estimated by the critical power model were used, subjects would have reached exhaustion at -8.0 [-19.4 to 3.3] % for the 10-min time trial, and at 13.3 [-2.8 to 29.5] % for the 20-min time trial. Thus, athletes and practitioners are encouraged to consider the specific work of the duration of interest at the severe intensity domain when monitoring with power in running.

Keywords Critical power · Work capacity · Endurance performance · Interval training

1 Introduction

The hyperbolic relationship of the power- or velocity-duration curve delimits the athletes' bioenergetics through its horizontal asymptote (i.e., critical power [CP] or critical velocity [CV]) and curvature constant (i.e., W' or D') [1]. These parameters are conceptually defined as the maximal work rate in which the metabolic stability is sustained and the work capacity remaining over it, respectively [2]. Any given intensity over CP or the second ventilatory threshold would, therefore, give rise to the development of the slow component of the oxygen uptake (VO_2), reaching exhaustion at its maximal amplitude (i.e., maximal oxygen uptake [$\text{VO}_{2\text{max}}$]), which delimits the severe intensity domain [2].

Given the practicability of transforming these physiological capabilities into objective data, a greater interest emerges from athletes and practitioners for its applicability in training design and competition planning. On one hand, in a competition context, the CP could represent the target work rate for continuous efforts lasting about

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30-min [3]. Likewise, any given intensity over CP would result in a time to exhaustion proportional to the W' depletion rate. Therefore, these parameters have been applied to the analysis of different long-distance track events, being able to properly determine the final position of each athlete according to their CP, W' , and the race pace [4]. On the other hand, in a training context, different empirical models have been proposed to model the balance between the W' depletion and recovery when the work rate is over or under CP, respectively [5]. Therefore, playing with the intensities and durations of the work and rest intervals, an athlete could be led to high levels of fatigue without reaching exhaustion (e.g., 80% W' depletion) [6].

However, the applicability of the CP concept to the training and competition planning is conditioned to the different nuances of the power duration curve modelling. It has been shown that CP and W' are subject to the CP model used [3, 7]. For example, Housh et al. [7] observed a difference in CP of up to 2.5 km/h (12.8–15.3 km/h) in recreational runners. Likewise, Ruiz-Alias et al. [3] reported that the CP was associated with different durabilities (20–30 min) in highly-trained runners. Regarding W' , wide ranges have been also reported (15–30 kJ) according to the CP model used [3]. Likewise, the W' parameter is characterized by a large standard error of the estimate (SEE), ranging from 9 to 25% [8–10], being at 10% the commonly acceptable threshold established [9, 10]. This means that having a SEE of 20% and performing an exercise bout that depletes W' to 80%, the athlete is at risk of reaching exhaustion prior to fully depleting W' .

To date, different training software packages such as the Golden Cheetah [11] or WKO software [12] bring closer to athletes and practitioners the CP concept. In these, users dispose different CP models and the analysis of the W' balance of an interval training session or race. Although the CP concept is applicable to all endurance disciplines, the vast evidence relies on the cycling field [13]. In running, this concept has been also widely used [14], although potential discrepancies might be observed when extrapolating these parameters (especially W') from the treadmill to the field [8, 15]. Considering the sensitivity of these parameters to slight changes in performance [8], its application in daily training is also subject to the precision of traditional GPS sports watches in tracking the running speed. Likewise, a hilly course alters the relationship between velocity and internal load, making unfeasible to monitor the actual work performed. In this regard, a growing interest is emerging in the running field on the power metric given its level of agreement with the external work and VO_2 , as well as its sensitivity and reliability among conditions (i.e., speed, body weight, and slope) and environments (i.e., indoor, outdoor) [16–19].

The existing theoretical framework for power-based running corroborates the use of the CP metric as the maximal metabolic steady-state given its proximity to the second ventilatory threshold [17]. Although different CP models have provided valid estimations when using the power metric in running [17], as observed in the cycling field, athletes and practitioners should be aware of the model used since significantly different CP values are observed [3]. Regarding W' , Ruiz-Alias et al. [3] have recently reported that the linear CP models were valid to predict the time to exhaustion associated with the power output performed on a 4-min running time trial. The other CP models overestimated by more than 4-min [3]. However, given the large SEE of this parameter reported in previous studies (9–25%) [8–10], it could be questioned if W' represents the potential work to be done above CP at all range of intensities along the severe intensity domain. Therefore, to increase the theoretical framework for power-based training in runners, this study aims to determine the validity of W' to represent the total work performed over CP on different time trials along the severe intensity domain.

2 Methods

2.1 Experimental design

Athletes performed four-time trials (i.e., 3-, 5-, 10- and 20-min) in a two-week training period. The order of the time trials was randomized and they were preceded by two light training days self-defined by the participants. The testing sessions were performed on a 400-m outdoor track, under similar environmental conditions (18–23 °C and 30–60% humidity), and time of the day (± 1 h). Athletes used the same own footwear for each time trial.

2.2 Participants

Fifteen highly trained athletes (8 males and 7 females, age: 23 ± 5 years, height: 166 ± 6 cm, body mass: 58 ± 8 kg, training volume: 110 ± 15 km per week; 5 km season-best: $15:29 \pm 00:53$) participated in the study. All athletes were informed about the research purpose and procedures of the study before signing a written informed consent form. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the institutional review board (No. 2288/CEIH/2021).

2.3 Time trials

Athletes began the testing sessions with a standardized warm-up which consists of 10-min of running at low-to-moderate intensity (i.e., intensity corresponding to easy

long-running sessions). After a series of dynamic mobility exercises, 3 high-intensity short bouts with 2-min of rest were done to complete the warm-up. Then, athletes began the time trial under the instruction of completing the longest distance possible. Four-time trials (i.e., 3-, 5-, 10- and 20-min) were performed on a 400-m outdoor track. To avoid any training effect, the order of the time trials was randomized. The pacing was self-selected and laps time feedback was given in every 400 m.

2.4 CP, W', and the work over CP in each time trial obtained with the power meter

The running power meter (Stryd Summit Power Meter, Boulder, CO, USA) was used to determine the mean absolute power output (W) of each time trial. The Stryd power meter has shown a high reliability indoors (coefficient of variation $\leq 2.8\%$) and outdoors (coefficient of variation $\leq 4.3\%$), for different external work conditions (i.e., speed, body weight, and slope), displaying also a high correlation with the VO_2 ($r \geq 0.911$) [16–19]. The body mass was measured with a weight scale (Seca 813; Seca Ltd, Hamburg, Germany) and updated daily in the power meter. This one was always attached to the laces of the right footwear. The CP and W' were determined through the $CP_{1/time}$ [20]:

$$PO = W' * (1/t) + CP$$

being PO the power output (In watts) and t the time (in seconds). The work over CP performed in each time trial was also determined $[(PO-CP)*t]$.

2.5 Statistical analysis

Descriptive data are presented as mean \pm standard deviation (SD) and 95% confidence intervals (CI). The normal distribution of the data and homogeneity of variances were confirmed through the Shapiro-Wilk test and Levene's tests, respectively. The W' obtained from the CP model was compared to the work performed over CP in each time trial through the paired sample t -test and Bland–Altman plots. The SEE of W' derived from the $CP_{1/time}$ was determined and established as the threshold of validity for accepting a similar work over CP of each time trial with respect to W' . Data analysis was performed using the software package SPSS (IBM SPSS version 25.0, Chicago, IL., USA). Statistical significance was set at $P \leq 0.05$.

3 Results

3.1 CP model

The CP and W' values as well as their associated SEE are reported in Table 1.

3.2 W' and the actual work over CP

Athletes performed the 3-min time trial at 132 (9.5) % of the CP (Table 2). The work performed over CP did not significantly differ from W' ($P = 0.748$; 65 [–359 to 488] J) (Fig. 1) which involved reaching exhaustion at 0.4 [–2.5 to 3.2] % of the W' . On an individual basis, 14 out of 15 athletes reached exhaustion within the SEE of W' (12.3 [9.9 to 14.7] %) (Fig. 2).

Athletes performed the 5-min time trial at 119 (4.7) % of the CP. The work performed over CP did not significantly differ from W' ($P = 0.385$; 489 [–681 to 1658] J) which involved reaching exhaustion at 0.3 [–9.6 to 10.3] % of W' . On an individual basis, 5 out of 15 athletes reached exhaustion within the SEE of W' (12.3 [9.9 to 14.7] %).

Athletes performed the 10-min time trial at 111 (4.0) % of the CP. The work performed over CP did not significantly differ from W' ($P = 0.096$; –1391 [–3061 to 278] J) which involved reaching exhaustion at –8.0 [–19.4 to 3.3] % of the W' . On an individual basis, 4 out of 15 athletes reached exhaustion within the SEE of W' (12.3 [9.9 to 14.7] %).

Athletes performed the 20-min time trial at 104 (1.7) % of the CP. The work performed over CP did not significantly differ from W' ($P = 0.058$; 2249 [–88 to 4585] J) which involved reaching exhaustion at 13.3 [–2.8 to 29.5] % of the W' . On an individual basis, 6 out of 15 athletes reached exhaustion within the SEE of W' (12.3 [9.9 to 14.7] %).

4 Discussion

The results revealed that the work capacity over CP is a variable rather than a fixed parameter. In particular, considering the SEE of the CP model, W' represented the

Table 1 Critical power (CP), work capacity over CP (W') and their associated standard error of the estimate (SEE) derived from the modelling of the power-duration curve (3-, 5-, 10-, and 20-min) with the $CP_{1/time}$

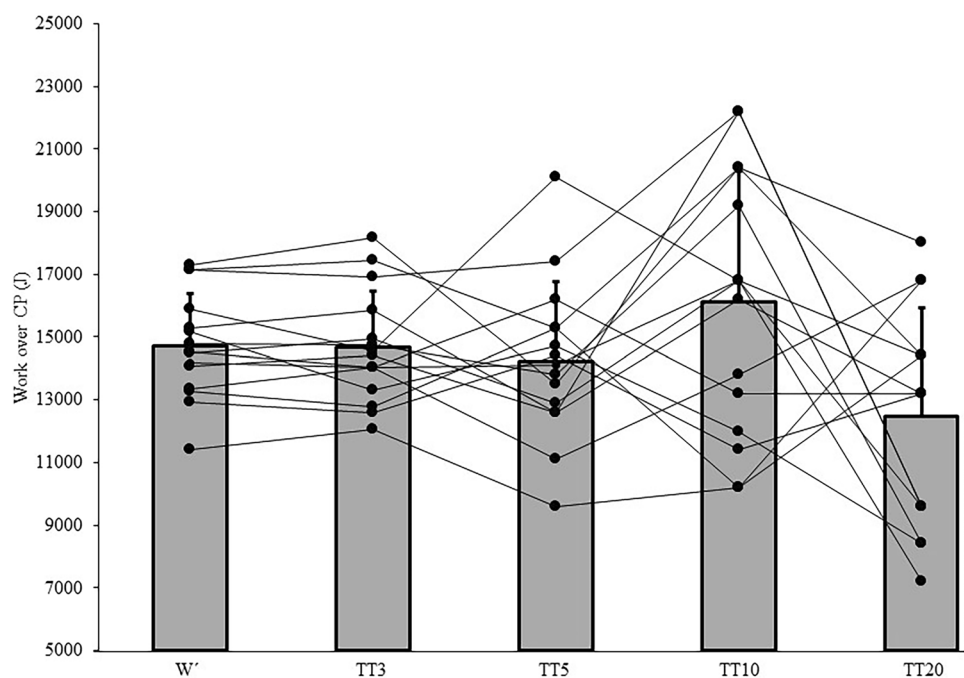
CP (W)	SEE (W)	SEE (%)	W' (J)	SEE (J)	SEE (%)
265 (59)	6.2 (2.5)	2.4 (1.0)	14729 (1670)	1829 (734)	12.3 (4.3)

CP Critical power, W' Work capacity over CP, SEE Standard error of the estimate

Table 2 Differences between the work capacity (W') over critical power (CP) derived from the modelling of the power-duration curve through the $CP_{1/time}$ and the work performed over CP in each time trial

Time trial	Intensity (% of CP)	W' (J)	Work over CP (J)	P -value	W' SEE (95% CI)	Bias (95% CI)	W' at exhaustion (%)
3 minutes	132 (9.5)	14729 (1670)	14664 (1780)	0.748	1829 (1457 to 2200)	65 (−359 to 488)	0.4 (−2.5 to 3.2)
5 minutes	119 (4.7)	14729 (1670)	14240 (2535)	0.385	1829 (1457 to 2200)	489 (−681 to 1658)	0.3 (−9.6 to 10.3)
10 minutes	111 (4.0)	14729 (1670)	16120 (4181)	0.096	1829 (1457 to 2200)	−1391 (−3061 to 278)	−8.0 (−19.4 to 3.3)
20 minutes	104 (1.7)	14729 (1670)	12480 (3448)	0.058	1829 (1457 to 2200)	2249 (−88 to 4585)	13.3 (−2.8 to 29.5)

SEE Standard error of the estimate, 95% CI 95% confidence interval

Fig. 1 Work capacity (W') over critical power (CP) derived from the modelling of the power-duration curve with the inverse of time CP model and the work performed over CP on each time trial

actual work performed over CP at the 3- and 5-min time trials, and it was under and overestimated at the 10- and 20-min time trials, respectively.

The SEE of W' was close to the validity criterion established in previous studies ($SEE < 10\%$) [9, 10]. It seems that this threshold corresponds to the accurate oxygen deficits reported when the SEE of W' was lower than 10% [21]. However, it should be noted that the time to exhaustion at the severe intensity domain does not only depend on the anaerobic metabolism [22]. Other factors such as the maximum VO_{2max} and the slow component of the VO_2 play a major role [23]. Other studies have also reported large SEE ranging from 9 to 25% [8–10]. Therefore, these values lead to the notion that W' is a variable rather than a fixed parameter.

This statement could be supported by those studies analyzing the effect of introducing different predicting trials to the CP model. In this regard, Triska et al. [8] determined CP and W' from three time trials of ~ 3.5, 6.7 and 17-min performed in laboratory and field conditions. The slight changes in performance observed in the three time trials (i.e., ~ 1.6-, 37- and 27-m) resulted in a questionable level of agreement of W' between conditions ($SEE: \sim 18\%$). Likewise, Triska et al. [24] determined W' using two different time trial combinations within the recommended 2- to 15-min range (i.e., 12-, 7-, 3-min vs. 10-, 5-, 2-min), obtaining moderate differences in W' (145- vs. 124-meter). Therefore, these discrepancies among W' estimates indicate that the work capacity over CP of each time trial introduced to the model is rather different. In the present study, the largest work over CP was

observed at the 10-min time trial (16.1 kJ), followed by the 5- and 3-min time trials (14.2 and 14.6 kJ) and, finally, the 20-min time trial (12.5 kJ). A similar trend was reported by Triska et al. [8] where the medium-time trial duration (~ 6-min: ~ 268-m) reported larger work capacities over CP than the longest (~ 17-min: ~ 213-m) and shortest durations (~ 3.5-min: ~ 207-m). Likewise, Mattioni-Maturana [25] reported a larger work capacity over CP at the medium-time trial duration (~ 7-min: ~ 17.9 kJ) compared to the longest (~ 19.4-min: ~ 11.6 kJ) and shortest durations (~ 1.7-min: ~ 15.5 kJ).

Any work rate performed at the severe intensity domain is characterized by a progressive drop in the metabolic stability, which gives rise to the development of the slow component of the VO_2 , reaching the limit of tolerance at its maximal amplitude (i.e., $\text{VO}_{2\text{max}}$) [6]. Therefore, W' size would be dictated by the rate at which the slow component of the VO_2 rises, the peak oxygen uptake ($\text{VO}_{2\text{peak}}$) reached, and the amount of non-oxidative energy used through the exercise [26]. According to the results here obtained, it seems that each W' determinant has a weighted factor depending on the exercise duration.

Although reaching the $\text{VO}_{2\text{max}}$ is a characteristic response of the severe intensity domain, different studies have reported lower $\text{VO}_{2\text{peak}}$ values for those efforts located closer to the CP [27, 28]. This has led to the notion of dividing this intensity domain in two, being W' size dictated either by the $\text{VO}_{2\text{max}}$ or by the ability to sustain a high fraction of the $\text{VO}_{2\text{max}}$ over the time [27]. The lower work capacity over CP observed at the 20-min time trial is in line with the evidence provided by the different studies that divide this intensity domain. In this regard, Bergstrom et al. [27] determined the CP of a group of moderately trained runners through four times to exhaustion lasting ~ 6-, 10-, 13- and 18-min on treadmill. The $\text{VO}_{2\text{peak}}$ values observed at the ~ 6- and 10-min times to exhaustion did not significantly differ from the $\text{VO}_{2\text{max}}$ value previously determined on an incremental test. On the other hand, the $\text{VO}_{2\text{peak}}$ reached at the 13- and 18-min times to exhaustion differed significantly, being located at 94 and 91% of $\text{VO}_{2\text{max}}$, respectively. Billat et al. [29] also reported in the group of high-level runners recruited no manifestations of the slow component of the VO_2 at intensities over CP (93% of $\text{VO}_{2\text{max}}$) lasting 17-min. Likewise, Sawyer et al. [28] observed significant differences between the $\text{VO}_{2\text{max}}$ previously determined in an incremental test on a cycle ergometer and the lowest intensity used to determine CP lasting 19-min (88% of $\text{VO}_{2\text{max}}$) in a group of physically active subjects.

It could be discussed if the lowest time trial used to define the CP model would be over or under the actual CP. According to our results, we have previously shown that for the CP model (i.e., $\text{CP}_{1/\text{time}}$) and predicting trials used (i.e., 3- to 20-min), the CP was similar to the one derived from

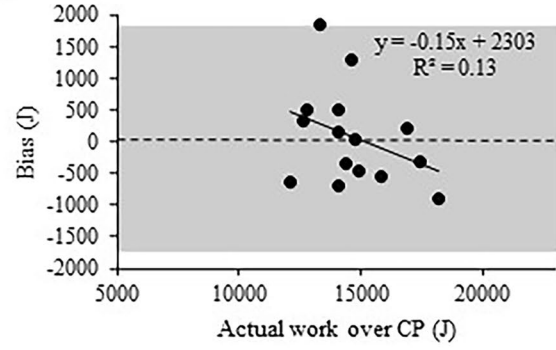
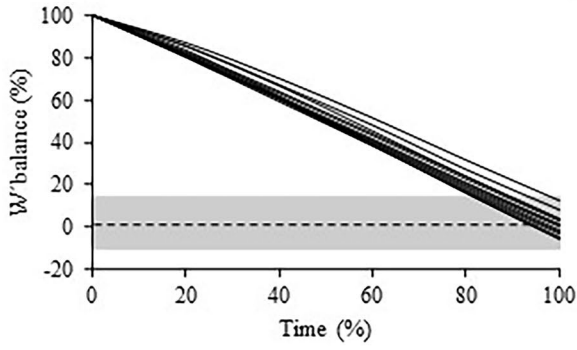
shorter efforts (i.e., 3- and 10-min) [30], placed at 30-min in the power duration curve [3]. In addition, considering the SEE of the CP parameter (2.4%) here reported, the 20-min work rate was over CP (104% of CP). Likewise, the aforementioned studies reporting lower $\text{VO}_{2\text{peak}}$ values at the longest duration reported a 5 to 10% higher work intensity with respect to CP [27–29].

According to the results here obtained, it seems that the work performed over CP has its apex in an intermediate duration of the severe intensity domain range. In this regard, Morton and Billat [31] reported that the 10-min resulted in the duration that elicited the maximal endurance time at $\text{VO}_{2\text{max}}$ across the range of velocities used to model the CP. Similar findings have been reported for the recommended duration of an incremental test to determine $\text{VO}_{2\text{max}}$, being maximized at 10-min and potentially underestimated at longer durations [32]. Likewise, significantly larger $\text{VO}_{2\text{max}}$ values have been reported for a maximal 10-min effort compared to the one reached at 2-min on a cycle ergometer in a group of physically active participants [33]. Therefore, considering the endurance model proposed by Morton and Billat [31], if similar $\text{VO}_{2\text{max}}$ values were reached on shorter efforts, longer durations at $\text{VO}_{2\text{max}}$ were reported for the 10-min time trial, resulting in a larger W' [33].

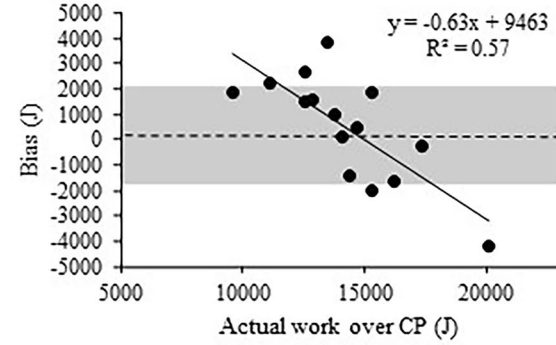
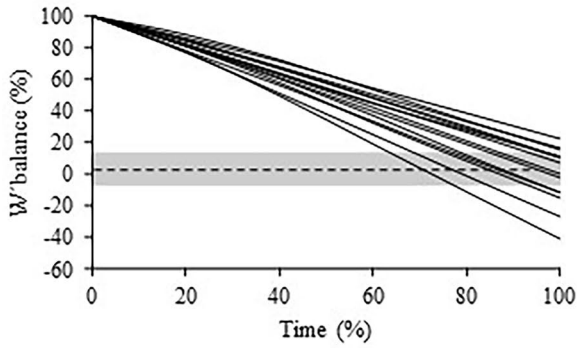
It is, therefore, not surprising that the use of W' has been criticized to estimate the time to exhaustion of a high-intensity interval training session. Galbraith et al. [34] determined CP and W' with a single-day field test composed of three trials (i.e., 3600-, 2400-, and 1200-m), and then assessed the level of agreement between the actual and estimated time to exhaustion of different interval training sessions of 1000-, 600-, and 200-meter intervals at 107, 110, and 150% of the CP with 200-meter recovery at 95, 90 and 80% of the CP through the linear W' balance model. Considering the SEE reported (> 40% of the actual time to exhaustion) [34], none of the interval training sessions would have been properly designed. The W' balance model could have been refined if the work capacity over CP of the work interval of interest was used rather than the W' of the CP model. Therefore, if CP and the actual W' are already known, only the W' reconstitution would remain to be determined. To this end, the Skiba et al. [35] function is actually available in the Golden Cheetah software, in which by an iterative process, the time constant at which W' is reconstituting can be determined to fit the W' expenditure to 0 at the point of exhaustion. Such time constant seems to vary according to the work and rest intensities and durations [34], whereupon future research lines should address this issue using the novel power metric in running.

Current power meters are a step forward in the athletes' monitoring. The low technological error displayed by these devices has led to the biological error being the main cause of the observed variability in the severe intensity domain

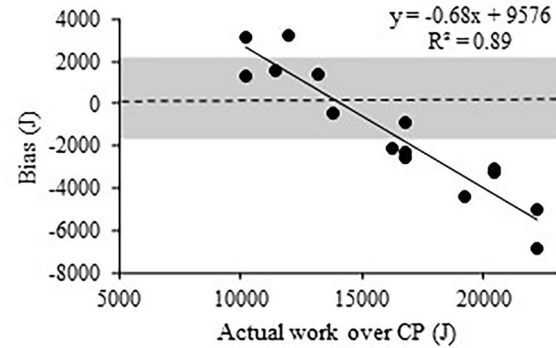
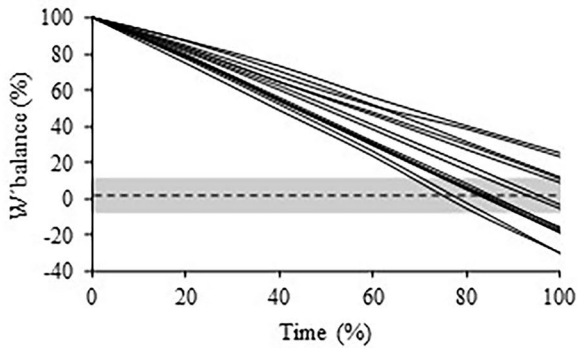
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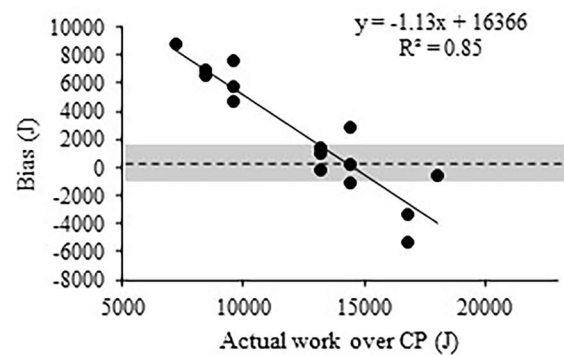
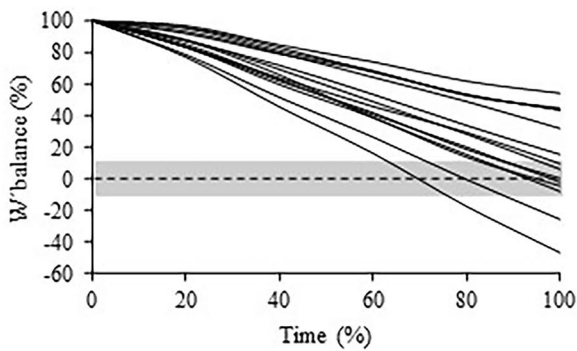
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TT10



TT20



◀**Fig. 2** Depletion of the work capacity (W') over critical power (CP) through each time trial and differences with the actual work performed over CP. The grey area represents the standard error of the estimate associated with W' (i.e., 1829 Joules or 12.3% of W'). R^2 : Coefficient of determination

[36]. Contemplating the analysis of further durations and populations could reveal relevant information for practitioners. Likewise, the between-day variability of efforts of the same duration should be contemplated to understand which thresholds should be considered as a result of a change in the athletes' performance status.

5 Conclusions

When using the power metric in running, athletes and practitioners should be aware that the work capacity over CP is a variable rather than a fixed parameter. In particular, this one seems to peak at intensities that reach exhaustion at 10-min, and drop at longer durations closer to CP (e.g., 20-min). Therefore, they should reconsider the use of W' for estimating the time to exhaustion at the severe intensity domain. On the other hand, W' does not cease to be an indicator of the athletes' performance status in conjunction with CP. To this end, based on the obtained results in this study, it is recommended to consider the work capacity over CP of the duration of interest rather than the one derived from the CP model.

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Data availability Data is accessible upon reasonable request from the corresponding author.

Declarations

Conflict of interest The authors declare no conflict of interest.

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