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How long can you run at critical power intensity? An analysis of the time to exhaustion in trained athletes

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Abstract: To date, speed has been the main external load variable in running, ignoring variables that can now be controlled by power. This means that concepts widely studied in cycling, such as critical power (CP), must now be deeply analyzed in running, considering the specificity of the discipline and the differences between both sexes. Thus, the aim of the study was twofold, i) to determine the individual time to exhaustion (TTE) at CP intensity in a group of highly trained athletes under field conditions and ii) to analyze the influence of sex in the TTE at CP. A local group of 37 highly trained athletes, 18 males and 19 females performed a CP test and a TTE test at CP intensity in two different field test sessions. Small ES but no significant differences ($p = 0.163$; ES: 0.45) between males (22.5 [6.9] minutes) and females (19.1 [7.8] minutes) were observed in the TTE test at CP. A high individual variability was observed, ranging the TTE from 9.2 to 32.5 minutes in males, and 9.3 to 36.1 minutes in females. This variability may be due to the standard error of the estimate.

Keywords: sex differences, field, performance, testing, endurance.

1. Introduction

Power meters have revolutionized the way cyclists train and compete (Allen & Coggan, 2012; Passfield et al., 2017) by providing reliable measurements of exercise intensity (Jeukendrup & Diemen, 1998). The

asymptote of the power-time relationship known as critical power (CP) determines the boundary between the heavy and severe intensity domains (Hill, 1993) which provides practitioners with a non-invasive



method for determining the maximum metabolic steady-state.

Given the relevance of the CP threshold in intensity management, power is gaining great attention in running settings due to its validity and reliability to reflect external work in diverse contexts (i.e., pace, gradient, body weight) (Cerezuela-Espejo et al., 2021; Imbach et al., 2020; Navalta et al., 2019; Pinedo-Jauregi et al., 2022). Specifically, among different commercial power meters, the Stryd device has been the most repeatable technology for different environments (indoor and outdoor) and conditions (speed, body weight, and slope). It also showed the best level of agreement to the VO₂ (Cerezuela-Espejo et al., 2021). Likewise, this device presents a strong and positive linear relationship with the power output derived from the force platforms (Imbach et al., 2020) as well as with the one reported by different theoretical models based on the laws of physics (Cerezuela-Espejo et al., 2020). Nevertheless, it is important taking into account the specificity of the discipline, since power would not be interchangeable between the cycling and running disciplines at CP intensity (Olaya-Cuartero, Pueo, Penichet-Tomas et al., 2023).

To date, speed has been the main external work variable in running (Billat, 2002). But currently, it is also important to consider that power is more relevant than ascensional speed to determine the metabolic demand at different gradients during running (Hingrand et al., 2023). In fact, given the sensitivity of the power metric to the different factors affecting external work, the use of this novel metric could provide athletes with a more precise way of regulating running intensity (Olaya-

Cuartero, Pueo, Villalon-Gasch et al., 2023). This issue is of great importance at certain intensities such as at CP, where a 5% difference could determine different metabolic responses (Hill et al., 2002; Poole et al., 1988). In this regard, previous articles determined critical speed (CS) and the time to exhaustion (TTE) at CS in laboratory settings, ranging between 10 to 32 minutes (Billat et al., 1998; Pepper et al., 1992). Given the growing interest in power and the CP metric in running (Dearing & Paton, 2022; Ruiz-Alias et al., 2022), this study aims to determine CP and the TTE at CP in highly trained male and female athletes in track. The sex comparison in this matter could be of great interest given that their physiological differences (Cheuvront et al., 2005; Santisteban et al., 2022) could derive from different durabilities at the same relative intensity (i.e., CP). Likewise, it is worth noting the ecological validity of testing in field conditions through this novel wearable device. According to the proximity of the CP of different CP models to the predicting trials (i.e., 10 to 30 minutes) (Ruiz-Alias et al., 2023b), it is hypothesized that the TTE for males and females could be located around this range.

2. Materials and Methods

Experimental design - Two testing sessions were used to determine CP and TTE at CP on a 400-meter track. On the first testing day, the CP intensity was determined through two-time trials of 9 and 3 minutes with 30 minutes of active recovery between them (Ruiz-Alias et al., 2022). After a resting period of at least 72 hours, each athlete performed a TTE test at the CP intensity (Figure 1). In the female group, no testing

sessions were conducted during the menstruation phase (Greenhall et al., 2020). Both testing sessions were conducted in the

field, respectively, with the same footwear at the same time of day (± 1 h).

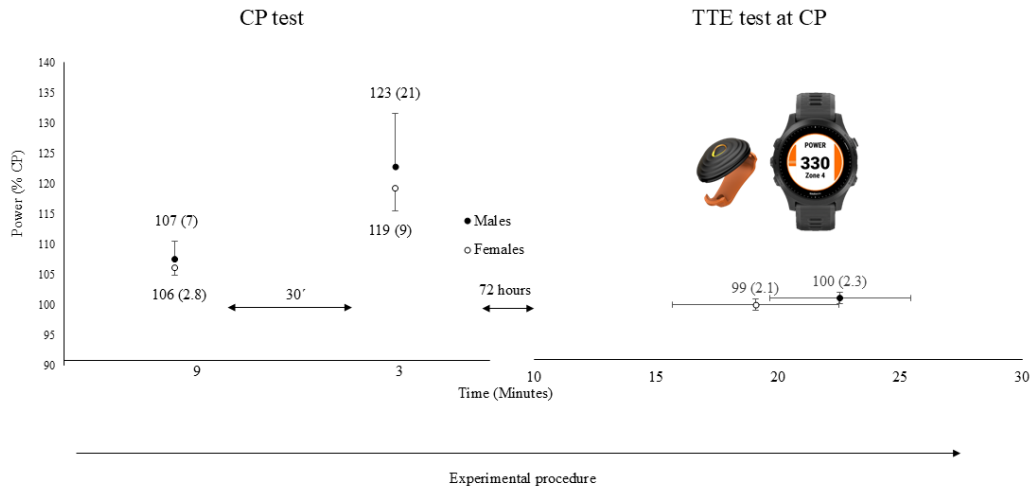


Figure 1. Differences between sexes in intensity and duration in the critical power (CP) and time to Exhaustion (TTE) tests. Mean and 95% confidence intervals are displayed.

Subjects —A total of 37 highly trained athletes, 18 males (Age: 26.7 [8.4] years; Weight: 69.4 [8.7] kg; Height: 174.5 [6.8] cm) and 19 females (Age: 29.1 [12.2] years; Weight: 58.2 [7.2] kg; Height 165.8 [5.0] cm) were recruited. All participants were members of a local training group with previous training experience in which they followed a structured and periodized training program. The following inclusion criteria were established to select highly trained athletes (McKay et al., 2021): (1) to perform a training volume > 150 minutes per week, (2) to identify with a specific sport, (3) to compete on a national level. Participants signed an informed consent form after being informed of the purpose of the study. The study protocol adhered to the Declaration of Helsinki and was approved by the institutional review board (No. 227/CEIH/2021).

CP Test—The following CP test has been validated in previous research (Ruiz-Alias et al., 2022). Athletes performed a warm-up of 10 minutes running at low to moderate intensity corresponding to easy long running sessions followed by 2 to 3 high-intensity 1-minute short bouts with 2 minutes of rest. Then, the running power meter was attached to the laces of the right shoe before conducting 2 maximum efforts of 9 and 3 minutes, respectively, with a 30-minute active recovery in between (Ruiz-Alias et al., 2022). A running power meter (Stryd Wind, Boulder, CO, USA) was used to determine the absolute (W) and relative power to weight (W/kg). The weight of the athletes was measured and updated in each testing session. This device, which estimates power in watts is a carbon fiber-reinforced foot pod that weighs 9.1 g and is based on a 6-axis inertial motion sensor (3-axis gyroscope and 3-axis accelerometer) (García-Pinillos et al.,

2021). The validity and reliability of this device are reported somewhere else (Baumgartner et al., 2021; Cerezuela-Espejo et al., 2021; Imbach et al., 2020; Navalta et al., 2019; Pinedo-Jauregi et al., 2022; Taboga et al., 2022). The values of the 9- and 3-minute time trials were subsequently entered into the Stryd CP calculator (<https://www.stryd.com/powercenter>) to obtain the CP value. According to the level of agreement between the Stryd CP model with the linear CP models (Ruiz-Alias et al., 2023b), it is expected that the Stryd CP calculator follows the same procedure of CP determination.

TTE at CP— The participants started with the aforementioned warm-up procedure. Before starting the test, they were informed about the CP intensity ($\pm 5\%$ of the target power) at which they had to perform the test. During the test, all participants had immediate feedback about the power via a Garmin Forerunner 935XT Watch (Garmin International, Inc., Kansas, United States). The test ended when the participants were unable to maintain the required power. To consider the test for analysis, two criteria had to be met: (1) the sustained intensity at the TTE test was within the CP intensity range ($\pm 5\%$ of the target power), and (2) the rating of perceived exertion (RPE) should be above 17 in the Borg-RPE Scale⁶⁻²⁰ (Borg, 1970).

Statistical Analysis— Descriptive statistics are represented as mean (SD). The Shapiro-Wilk test was applied to confirm the normal distribution of the data whereas the Levene test was applied to confirm the homogeneity of variances. An independent samples t-test was performed to analyze the differences between sex groups. The Hedges' g effect size (ES) was calculated and

interpreted as follows: trivial (< 0.20), small ($0.20-0.59$), moderate ($0.60-1.19$), large ($1.20-2.00$), and extremely large (> 2.00) (Hopkins et al., 2009). The coefficient of determination (R^2) (Motulsky & Christopoulos, 2004) was conducted between relative CP (W/kg) and TTE (minutes) for each sex. A power analysis was conducted for a two-sided independent samples t-test using the Power Analysis module in JASP (version 0.96). Assuming a medium effect size of $|\delta| = 0.50$ (Cohen, 1988) and a significance level of $\alpha = .05$, the available sample of 18 males and 19 females provides an approximate power of $1 - \beta = 0.32$ to detect such an effect, interpreting the ES and the confidence intervals (CI) in the statistical results. Statistical analyses were 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

Time trials to determine CP— The descriptive values of the 9 and 3 minute time trials are indicated in Table 1. No significant differences were reported between males and females at the relative intensities of both time trials (9 minutes: $p = 0.409$; ES: 0.19 [-0.48 to 0.85], 3 minutes: $p = 0.499$; ES: 0.24 [-0.43 to 0.92]).

	Males (N= 18)	Females (N= 19)	P-value	ES (95% CI)
9' (meters)	2658 (297)	2148 (287)	<0.001	1.71 (0.92 to 2.50)
9' (% CP)	107 (7.0)	106 (2.8)	0.409	0.19 (-0.48 to 0.85)
3' (meters)	988 (128)	820 (111)	<0.001	1.37 (0.63 to 2.12)
3' (% CP)	123 (21)	119 (9)	0.499	0.24 (-0.43 to 0.92)
CP (W/kg)	4.7 (0.58)	3.9 (0.49)	<0.001	1.46 (0.71 to 2.22)
TTE (% CP)	100 (2.3)	99 (2.1)	0.155	0.44 (-0.23 to 1.12)

TTE (meters)	6411 (2360)	4496 (2229)	0.016	0.82 (0.12 to 1.51)
TTE (minutes)	22.5 (6.9)	19.1 (7.8)	0.163	0.45 (-0.23 to 1.13)

Table 1. Distances and intensities performed in the CP and TTE at CP tests. Mean (SD); CP: Critical power; TTE: Time to exhaustion; ES: Effect size; CI: Confidence interval.

TTE at CP— The TTE at CP ranged between 9.2 to 32.5 minutes in males, and between 9.3 to 36.1 minutes in females. No significant differences were observed between the intensities performed by males and females in the TTE test at CP (Males: 100 [2.3] % CP; Females: 99 [2.1] % CP; $p = 0.155$; ES: 0.44 [-0.23 to 1.12]). No significant differences were observed between the males and females in the TTE (Males: 22.5 [6.9] minutes; Females: 19.1 [7.8] minutes; $p = 0.163$; ES: 0.45 [-0.23 to 1.13]).

To explore potential predictors of the observed TTE variability, the coefficient of determination (R^2) was conducted between relative CP (W/kg) and TTE (minutes) for each sex (males: $R^2 = 0.0184$; females: $R^2 = 0.0998$), suggesting that relative CP alone would not explain the interindividual variability in TTE (Figure 2).

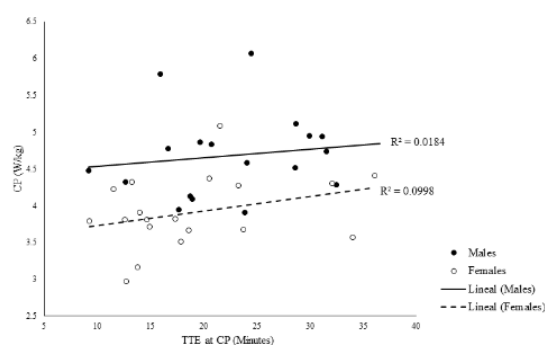


Figure 2. Coefficient of determination between relative CP and TTE.

4. Discussion

This study aimed to determine the CP and the TTE at CP in highly trained male and female athletes. The results reveal that the

TTE at CP is around ~23 and 19 minutes in highly trained male and female athletes, respectively. A high individual variability was observed, ranging the TTE from 9.2 to 32.5 minutes in males, and 9.3 to 36.1 minutes in females. This issue could be related to the standard error of the estimate.

The TTE at CP here reported matches with the TTE reported in previous studies at CS (Billat et al., 1998; Pepper et al., 1992). Pepper et al. (1992) recruited a group of 10 male adults to perform 4 TTE treadmill runs to determine CS through the linear distance-time model (Moritani et al., 1981). A mean TTE of ~16 minutes was observed, ranging between 10 to 32 minutes (Pepper et al., 1992), in line with the variability here reported. In the same way, Billat et al. (1998) recruited a group of 14 high-level long-distance runners to perform 3 TTE treadmill runs to determine CS through the linear distance-time model (Moritani et al., 1981). The study found a TTE of 17 minutes, varying from 10 to 23 minutes.

The main challenge when analyzing the TTE at CP is to accurately determine this threshold. Different CP values have been reported according to the model used (Housh et al., 2001). Likewise, the time trials combination could also condition the CP metric (Maturana et al., 2018). Therefore, in the present study, the CP was determined according to a valid protocol (Ruiz-Alias et al., 2022). The authors employed two-time trials of 9 and 3 minutes with 30 minutes of active recovery to determine CP through the Stryd power meter software, finding non-significant differences with the respiratory compensation point (RCP) (i.e., the minimal load at which the increase in the ventilatory equivalent of oxygen is encompassed by the increase of the ventilatory equivalent of carbon dioxide) (Wasserman & McIlroy, 1964), determined in a graded exercise test. Interestingly, Dearing and Paton (2022) also obtained strong correlations with the RCP

when determining the CP through the training history of the previous 90 days in which the Stryd software searched for the best long (40-60 minutes), medium (10-20 minutes), short (3-5 minutes) and sprint (10-30 seconds) performances. Therefore, this simplified protocol enables practitioners to determine the CP during a single testing session, and according to the results obtained here, it also reveals the maximum work rate that can be sustained for maximal efforts lasting nearly 20 minutes.

However, a critical methodological consideration concerns the standard error of the estimate (SEE) inherent to the two-point CP model used in this study. It is well established that two-point protocols yield higher SEE than models derived from three or more time-trial durations (Maturana et al., 2018; Ruiz-Alias et al., 2023a), as the use of only two data points does not allow residual variance to be estimated independently. Although the 9/3-minute protocol has been validated against the respiratory compensation point (Ruiz-Alias et al., 2022), individual CP estimates may deviate from the true physiological threshold by a non-trivial margin. Given the hyperbolic nature of the power-duration relationship, even a modest misestimation of CP (e.g., $\pm 5\%$) can result in substantially different TTE outcomes, potentially accounting for differences of 5 to 15 minutes at the individual level (Maturana et al., 2018). It is therefore plausible that a meaningful proportion of the wide TTE range observed (9 to 36 minutes) reflects variability in the precision of individual CP estimates rather than true interindividual differences in physiological durability. Maybe for this reason, future research should examine TTE at CP determined through three or more time-trial durations to quantify the independent contribution of SEE to TTE variability.

The results show a common TTE range of 9 to 36 minutes for both male and female athletes, but the level of the athletes should also be taken into consideration. According to Jones and Vanhatalo (2017), male long-distance elite athletes can complete a marathon at intensities close to CS, which requires a TTE of over 120 minutes, suggesting that TTE at this intensity can be improved with training. Similarly, and more specifically, the CP target at which a half-marathon can be run by male-trained athletes is estimated to be approximately 97.3% previously determined by the 9/3-minute Stryd CP test (Olaya-Cuartero, Pueo, Villalon-Gasch et al., 2023).

Although the study provided insightful findings, some limitations need to be acknowledged. First, the two-point CP model employed carries an inherent standard error of estimate that could not be independently quantified in this study, as only two data points were available per athlete. This limits the precision of individual CP estimates and may have contributed to the observed variability in TTE. Second, the exhaustion criterion relied on two conditions: sustained intensity within $CP \pm 5\%$ and $RPE \geq 17$ on the Borg 6–20 scale. While widely used in field-based research, RPE carries substantial inter-individual variability and may not unambiguously indicate true volitional exhaustion at the CP boundary in all participants (Borg, 1970). The absence of objective physiological markers of maximal effort, such as post-exercise blood lactate concentration or peak heart rate relative to individual maximum, represents a limitation of the present study and should be addressed in future research through the inclusion of both subjective and objective exhaustion criteria.

5. Practical Applications

Practitioners should be aware of the limitations of the study. The testing

procedure to determine the CP was based on two maximal efforts of 9 and 3 minutes. It has been previously reported that selecting different two-time trial durations could differ significantly (Ruiz-Alias et al., 2023a), to which practitioners should pay attention as it would condition the TTE expected. The use and application of devices such as these running power meters open a new research paradigm applicable to the control of intensity through another objective variable that serves as an alternative to pace, which to date has been the main indicator of external load in this sport (Billat, 2002).

6. Conclusions

The results revealed that the TTE at CP is around ~23 and 19 minutes in highly trained male and female athletes, respectively. The observed range indicating endurance at CP is between durations of 9 and 36 minutes.

Devices such as the Stryd power meter open up a range of possibilities for coaches and athletes to determine and regulate different running intensities as an alternative to pace.

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