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Novelty bullets: points that summarize the key findings in the work:	Critical power (CP) calculation enables to predict time to exhaustion (TTE) at any cycling power-output., We tested those predictions against measured TTE in a wide range of cycling power-outputs., CP appropriately predicted TTE at VO2max intensity but err at higher and lower cycling power-outputs.
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Time to exhaustion during cycling is not well predicted by critical power calculations

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ABSTRACT

Three to five cycling tests to exhaustion allow prediction of time to exhaustion (TTE) at power output based on calculation of critical power (CP). We aimed to determine the accuracy of CP predictions of TTE at power-outputs habitually endured by cyclists. Fourteen endurance-trained male cyclists underwent 4 randomized cycle-ergometer TTE tests at power-outputs eliciting, *i*) mean Wingate anaerobic test ($WAnT_{mean}$), *ii*) VO_2max, *iii*) respiratory compensation threshold (VT_2) and *iv*) maximal lactate steady state (MLSS). Tests were conducted in duplicate with coefficient of variation of 5-9%. Power-outputs were 710±63 W for $WAnT_{mean}$, 366±26 W for VO_2max, 302±31 W for VT_2 and 247±20 W for MLSS. Corresponding TTE were 00:29 ± 00:06, 03:23±00:45, 11:29±05:07 and 76:05±13:53 mm:ss, respectively. Power output associated with CP was only 2% lower than MLSS (242±19 vs. 247±20 W; $P<0.001$). The CP predictions overestimated TTE at $WAnT_{mean}$ (00:24 ± 00:10 mm:ss) and MLSS (04:41 ± 11:47 mm:ss), underestimated TTE at VT_2 (-04:18 ± 03:20 mm:ss; $P<0.05$) and correctly predicted TTE at VO_2max. In summary, CP accurately predicts MLSS power output and TTE at VO_2max. However, it should not be used to estimate time to exhaustion in trained cyclists at higher or lower power-outputs (e.g., sprints and 40 km time trials).

Novelty bullets:

- Critical power (CP) calculation enables to predict time to exhaustion (TTE) at any cycling power-output
- We tested those predictions against measured TTE in a wide range of cycling power-outputs.
- CP appropriately predicted TTE at VO_2max intensity but err at higher and lower cycling power-outputs.

Key words: Endurance training; Wingate anaerobic test; Respiratory compensation point; VO_2max; Maximal lactate steady state; Cyclist.

INTRODUCTION

Exercise intensity and duration are the key factors in the prescription of endurance training (Seiler 2010; Seiler and Sjursen 2004). Exhaustion limits duration of exercise and it is inversely related to exercise intensity either when measured by power output (cycling) or velocity (running, rowing or swimming). A.V. Hill (Hill 1925) using running and swimming world records over a variety of distances in men and women first defined the hyperbolic relationship between velocity and duration. However, the importance of the asymptote of that hyperbolic relationship (i.e., definition of critical power) was first noticed by Monod and Scherrer (Monod and Scherrer 1965) more than 50 years ago. Since then, power/velocity versus time to exhaustion (TTE) relationships using different locomotion modes (i.e., running, cycling, swimming) have been measured often in the scientific literature allowing calculation of critical intensity of exercise, which when measured in watts it is termed critical power (i.e., CP; (Poole and Barstow 2015)). CP demarcates the highest power output at which cellular homeostasis can be sustained. Even slight deviations from that power output result in decreased performance. In addition, the curvature constant of the hyperbolic relationship represents the work capacity available above CP (i.e., W' measured in Joules).

CP calculations could be used to predict TTE at any given power output above CP (Jones and Vanhatalo 2017) which has enormous potential applications to training. CP theoretically defines the threshold beyond which muscle metabolites (i.e., phosphocreatine, and hydrogen ions) blood lactate concentration, and whole-body oxygen uptake (VO_2) lose homeostasis. TTE derived from CP calculations provides a versatile tool for fitness assessment, monitoring the impact of endurance training or ergogenic aids interventions (Vanhatalo et al. 2011). Prescription of exercise intensity relative to CP could result in a more homogenous response than classical approaches based on percentage of maximal oxygen consumption (Iannetta et al. 2019c; Mann et al. 2013). CP could be used to calculate athletes' best possible time for a given distance and to consider pacing approaches in a race (Jones et al. 2010; Vanhatalo et al. 2011) although CP could be influenced by previous activity (Clark et al. 2019; Iannetta et al. 2018). Avoiding frequent deviations from CP during a race (i.e., maintaining constant pace) would prevent the associated muscle metabolic and systemic alterations that would lead to exhaustion. In fact, analysis from racing times in different distances reveals that critical velocity in running (i.e., surrogate of CP when running) is at 96% of the marathon speed in elite athletes (Jones and Vanhatalo 2017). CP has been associated with the respiratory compensation point (RCP; (Keir et al. 2018a)) and the maximal lactate steady state (MLSS; (Keir et al. 2018b; Pringle and Jones 2002)). However, the applicability of CP to provide intensity and duration advice for training has not been yet proven.

To obtain CP, typically subjects complete between 3 and 5 separated exercise TTE tests on different days. The power-outputs are selected to result in exhaustion in a minimum of 2 min and a maximum of 15 min (Morton 2006). Thus, determination of CP requires a series of 3-5 constant work rates to failure usually separated by 24 h recovery, making determinations lengthy. In addition, CP and W' are affected by the mathematical model used in the calculations (i.e., linear vs. nonlinear; 3 vs. 2 parameters hyperbolic model; (Bishop et al. 1998)), the duration of the TTE trials (Mattioni Maturana et al. 2018), the recovery time between test (i.e., 30 min vs. 24 hours; (Karsten et al. 2017)) and the nature of the test (i.e., constant work rate to exhaustion or time trial with a target time limit; (Black et al. 2015)). Regarding the mathematical model, the 3 parameter hyperbolic model seems to derive the lowest CP and the highest W' compared to the other models (Bergstrom et al. 2014; Bull et al.

2000; Gaesser et al. 1995; Mattioni Maturana et al. 2018). Bishop and coworkers detected that if data from 5 TTE trials were rearranged and only the 3 tests with the shortest duration were considered, CP was 14-20% larger than the derived from the 3 longest durations (Bishop et al. 1998). Furthermore, investigators have wondered if CP correctly predicts TTE in cycling bouts as short as 20 seconds (Vinetti et al. 2019) or beyond 15 min (Sawyer et al. 2012).

CP calculation could provide coaches with the ability to prescribe training duration in a wider range of training intensities. However, different methodological approaches to the measurement of CP and W' limit its standardization. Furthermore, it is unclear if CP measured using TTE trials between 2 and 15 min can accurately predict cycling performance in bouts lasting less than 1 min (i.e., all out sprints) or above 30 min (i.e., common time-trials). The purpose of this study was to determine if CP (using the 4 tests and the 2-parameter model) accurately predicts TTE at high and low power-outputs typically endured by trained cyclists. The ultimate goal is to advise cycling coaches on the use of CP as a training tool.

MATERIALS and METHODS

Subjects. Fourteen trained men cyclists and triathletes volunteered to participate in this study with characteristics as listed in Table 1. They were recruited from local cycling and triathlon clubs. Measurements were obtained during the pre-competitive season. All participants underwent a complete medical examination (including ECG) that showed all were in good health. None of the subjects were taking drugs, medicaments, or dietary supplements known to influence physical performance. The Bioethics Commission of a local University approved the study, which was carried out according to the declaration of Helsinki. Subjects were verbally informed about the experimental procedures and possible risk and benefits. Written informed consent was obtained from all subjects.

Study Design. Participants performed only one test per day with 48-72 h separation among tests. On the first day they underwent a graded exercise tests (GXT) and a complete medical examination (including ECG) geared to, a) confirm normal cardiac functioning, b) familiarized subjects with testing equipment, c) discard participants with VO_2max lower than 47.0 $ml·kg^{-1}·min^{-1}$. Following GXT, participants avoided intense training (i.e., training at heart rates > 70% of maximal heart rate) during 48 hours before performing a Wingate anaerobic test ($WAnT_{mean}$). After that, subjects performed a second GXT to identify the average power output (W) associated with the attainment of VO_2max and VT_2 when using an incremental test of 25 $W·min^{-1}$ stages (Lucia et al. 2000). Then, in a random order, participants underwent, in separated days, two identical TTE tests at power outputs of $WAnT_{mean}$, VO_2max and VT_2 to ensure reproducibility in our measurements. Finally, participants visited the lab 3 more times to determine the power output associated with MLSS, followed by two tests until exhaustion at MLSS power output (Figure 1). Trials took place at the same time of day for each subject to avoid circadian rhythm effects (Mora-Rodriguez et al., 2015). Trials were held under constant laboratory environmental conditions (i.e., 22.0 ± 2.2°C, 44.8 ± 8.9% relative humidity, wind cooled at 2.55 $m·s^{-1}$). All of them were asked to keep their eating habits constant following a similar type of high-carbohydrate (CHO) diet during the days before testing.

TTE tests. Except for $WAnT_{mean}$ all tests were performed using the subjects' own training road bicycle set on a Cycleops Hammer® indoor trainer controlling power output in a cadence independent mode (Lillo-Bevia and Pallares 2018). During the tests, subjects could see and choose their preferred cadence but were kept blinded to any other variable (i.e., elapsed time, lactate, heart rate, etc.). All tests started with five minutes of warm-up. Then, trial target power output was set while RPE, heart rate and cadence were recorded frequently (every 5 min and every 5 seconds during $WAnT_{mean}$). TTE was recorded when subjects were unable to maintain cycling cadence above 60 revolutions per minute. Starting at 20 min into the MLSS trials, participants ingested ~125 ml of water every 10 min to avoid dehydration. Following exercise, subjects cooled down at 75 W for 5 minutes.

Wingate test. Wingate test was performed in a mechanically braked cycle ergometer (Monark©) adapted with clipless pedals and a calibrated power-meter crank (Professional, SRM, Jülich, Germany). Saddle and handle-bar positions were adjusted to approximate each subject's own bike. Subjects warmed up for 5 min at a self-selected intensity followed by two 5 second familiarization sprints, interspersed by 30 seconds of easy cycling. Starting from a stop, subjects completed 30-seconds all-out effort against a frictional resistance of 0.075 $kg \cdot body\ mass^{-1}$. Subjects were required to remain seated and were verbally encouraged throughout the test. The mean power output during the 30 seconds ($WAnT_{mean}$) was recorded.

Graded exercise tests (GXT). Immediately following a standardized a warm-up of 5 min at 50 W, all participants performed a ramp protocol with increments of 25 $W \cdot min^{-1}$ until exhaustion (Lucía et al., 2000) with a free chosen cadence. During GXT oxygen consumption (VO_2) and carbon dioxide production (VCO_2) were recorded using breath-by-breath indirect calorimetry (Cortex Metalyzer 3B, Leipzig, Germany), which was calibrated before each test. Heart rate was continuously monitored (Polar Bluetooth H7, Finland). Capillary blood samples were obtained at the beginning (basal values) and three minutes after tests ending to assess lactate concentration (Lactate

Pro2, Arkray, Japan). Each participant indicated their rate of perceived exertion at every stage (Borg 1982).

Power output at VO_2max and VT_2. The minimal power output that achieved VO_2max was identified. VO_2max attainment was confirmed by an increase in VO_2 between two consecutive stages below 1.5 $ml \cdot kg^{-1} \cdot min^{-1}$ or by secondary criteria (i.e., RER≥ 1.10, HR_{max}> 95% age-predicted maximum). For VT_2 determination ventilation parameters during GXT were averaged every 1-min and plotted against power-output. VT_2 was determined using the criteria of an increase in both the V_E/VO_2 and V_E/VCO_2 and a decrease in end-tidal pressure of carbon dioxide ($PetCO_2$; (Lucia et al. 2000)). Two experienced investigators detected VT_2 and in the case of disagreement, a third investigator analysis was obtained.

At workloads above lactate threshold (or gas exchange threshold) the slow component of the VO_2 kinetics emerges (Jones et al. 2011) and determination of workload at VT_2 and VO_2max depends on stage duration and magnitude of work rate increases per stage of the incremental protocol (Iannetta et al. 2019c; Keir et al. 2018b). Those recent publication have brought to our attention that it is incorrect to assign a fixed workload to VT_2 and VO_{2MAX} or a fixed VO_2 to VT_2 since it will drift up to VO_2max. Thus, the workloads presented in this study at VT_2 and VO_2max only pertain to the 25 watt per min incremental test presently used and should not be taken as a workload training advice.

Power output at MLSS. Several 30-min constant power output trials were initially performed to identify the highest power output at which blood lactate concentration increased less than 1 mmol between 10 and 30 min of cycling. The initial MLSS trial was performed at 70% of the individual VO_2max power output (Lillo-Bevia et al. 2019). Second and subsequent MLSS tests were increased or decreased by 0.2

$W \cdot Kg^{-1}$ (~ 15 W; (de Barros et al. 2011)), until criterion was fulfilled. Recent data suggest that 10 W are already enough to elicit changes in MLSS (Iannetta et al. 2018) however we decided to use 0.2 $W \cdot Kg^{-1}$ to be consistent with previous studies from our group. Approximately 3 tests were necessary to determine MLSS power-output.

Calculation of CP, W' and TTE. Power output in watts during the 4 trials was multiplied by trial duration in seconds of the first set of repeated tests to obtain work in joules. The work accomplished in each trial was plotted against the time to exhaustion measured ($TTE_{measured}$) and the *y*-intercept of that line represented W' while the slope represented CP:

$$\text{Work} = W' + (CP \times TTE_{measured})$$

Once CP and W' were obtained for each individual, the calculated time to exhaustion (i.e., $TTE_{calculated}$) at each power output was found using the following equation (Hill 1993):

$$TTE_{calculated} = W' / (\text{Power} - CP)$$

where W' is the curvature constant that represents the work capacity available above CP measured in joules (Monod and Scherrer 1965). We chose the 2-parameter hyperbolic model that assumes that the time axis asymptote is zero since estimation of maximal power output to calculate this asymptote (3-parameter hyperbolic model) introduces more variability to the calculations (Muniz-Pumares et al. 2019).

We chose a CP protocol using 4 trials because time to exhaustion trials of varying duration should be used to minimize the influence of shorter trials when modelling CP (Bishop et al. 1998). However, time to exhaustion during the MLSS trial is beyond 1 h and such a long trial has not previously used to calculate CP. This may create some methodological artifact in the calculation of CP. Furthermore, we chose the 2-parameter model because the 3-parameter model requires measurement of maximal instantaneous power using special cycle ergometers or extrapolation by vertical jump on a force platform (Vinetti et al. 2019). Thus the 2 parameter model is he most commonly used CP model in sports science and exercise physiology due to its simplicity and accuracy in performance predictions (Jones and Vanhatalo 2017).

Statistical analysis. Standard statistical methods were used for the calculation of means, standard deviations (SD). Data were screened for normality of distribution and homogeneity using a Shapiro-Wilk normality test and a Levene test, respectively. To analyze the TTE within-subject reliability, CV and ICC were calculated. Differences between $TTE_{calculated}$ (first set of tests) and the $TTE_{measured}$ (second set of tests) using CP and W' for each trial, were detected using paired Student t-test. Analyses were performed using commercially available software GraphPad Prism 6.0 (GraphPad Software, Inc., CA, USA). Significance was set at an alpha level ≤ 0.05.

RESULTS

Physiological indexes of exhaustion. Subjects were endurance-trained cyclists and triathletes with more than 5 years of training experience (Table 1). Suggesting that subjects drove themselves to exhaustion in all trials the following variables reached high values; RPE was above 17 units in all trials, capillary blood lactate reached concentrations above 10 mM in the VO_2max and VT_2 trials and HR was above 170 beats·min^{-1} in all trials except MLSS (Table 2).

Cycling power and TTE. Power output was 710 ± 63 W for $WAnT_{mean}$, 366 ± 26 W for VO_2max, 302 ± 31 W for VT_2 (when using an incremental test of 25 W·min^{-1} stages) and 247±20 W for MLSS. Calculated CP power output was only 0.4% lower than MLSS (242 ± 19 vs. 247 ± 20 W) although, that difference was consistent in all 14 subjects and thus statistically significant ($P<0.001$; Figure 2). Measured times to exhaustion ($TTE_{measured}$) using the second set of test, were 00:29 ± 00:06 at the power at $WAnT_{mean}$, 03:23±00:45 at the power at VO_2max, 11:29±05:07 at the power at VT_2 and 76:05±13:53 mm:ss at the power at MLSS, respectively. With the first set of tests, we calculated times to exhaustion ($TTE_{calculated}$) using the individually derived CP and W' and were 00:52 ± 00:12 at $WAnT_{mean}$, 03:15 ± 00:31 VO_2max, 07:11 ± 02:28 at VT_2 and 80:24 ± 18:37 mm:ss at MLSS.

Differences between $TTE_{calculated}$ and $TTE_{measured}$. $TTE_{calculated}$ overestimated $TTE_{measured}$ at $WAnT_{mean}$ by 86% (00:24 ± 00:10 mm:ss; $P< 0.001$). The calculated and measured TTE were similar (i.e., 1% difference) at the power at VO_2max (00:08 ± 00:41 mm:ss; $P = 0.493$). $TTE_{calculated}$ underestimated $TTE_{measured}$ at VT_2 by 34% (-04:18 ± 03:20 mm:ss; $P< 0.001$). Finally, $TTE_{calculated}$ overestimated $TTE_{measured}$ by 6% at MLSS (04:41 ± 11:47 mm:ss; Figure 3).

Reliability. Between the two repeated set of trials, CV was lowest for $TTE_{measured}$ at MLSS (CV = 5.4%) and increased as exercise intensity increased to 7.0%, 6.9% and 7.6% for the VT_2, VO_2max and $WAnT_{mean}$, respectively. ICC values for $TTE_{measured}$ were high ranging from 0.766 to 0.946. However, between-subject reliability of the $TTE_{measured}$ at the different intensities revealed a moderate to high CV ($WAnT_{mean}$ = 24%; VO_2max = 19%; VT_2 = 44%; MLSS = 18%).

DISCUSSION

To deliver science-based individualized training prescription, knowledge of the time limit (time to exhaustion, TTE) at different power-outputs (or velocities) is important. Traditionally, TTE can be estimated by fitting to a hyperbolic curve the results of 3-5 exercise tests to exhaustion at power-outputs that elicit exhaustion between 2 and 15 min (i.e., critical power, CP calculations). However, there are concerns regarding the trustworthiness of those TTE estimations at power-outputs lower than 2 min (Vinetti et al. 2019) or higher than 15 min (Black et al. 2017; Jones et al. 2019). The incorrect estimation of TTE could err training advice resulting in prescribing exercise bouts either too short to elicit training adaptations, or too demanding leading to early exhaustion or overtraining. We found that the $TTE_{calculated}$ using CP overestimated duration both at high ($WAnT_{mean}$, 710 ± 63 W) and low power-outputs (i.e., MLSS 247 ± 20 W) in trained cyclists. The overestimation represented 11% (i.e., 9 min) at MLSS power output (Figure 3). Training at MLSS intensities according to CP calculations would result in 11% more training time. However, since MLSS appears at relatively low power-outputs (i.e., 68±3% of VO_2max power output) it is unlikely that the extra duration would enhanced aerobic adaptations in well-trained athletes (Lorenzo et al. 2010). In contrast, $TTE_{calculated}$ at VT_2 power output (i.e., 302 ± 31 W) underestimated by 34% (i.e., 4:18 min) the measured TTE.

Endurance training heavily relies on bouts at power-outputs close or above VT_2 (Coyle et al. 1991; Esteve-Lanao et al. 2007; Seiler 2010) and thus this underestimation could have a large impact on training adaptations. Using $TTE_{calculated}$, (CP and W') training bouts at VT_2 will be shortened and thus the expected training adaptations not reached. However, recent findings reveal that the power output associated with VT_2 when using a ramp protocol should not be used to prescribe constant-load exercise since VO_2 slow component would progressively increase the metabolic demand (Iannetta et al. 2019b; Keir et al. 2018b). So, it is uncertain if this difference between the TTE calculated by CP and the actually measured, is relevant in the context of a drifting VO_2. Finally, power training cycling sprints at WAnT workloads (710 ± 63 W) based on $TTE_{calculated}$ will be too demanding (almost 1-fold TTE overestimation; 29 ± 6 to 52 ± 12 seconds) driving cyclists to premature exhaustion and risking overtraining or injury.

We found that the power output associated with CP was statistically smaller than that observed at MLSS, although the absolute difference was only a 2% (i.e., 242 ± 19 vs. 247 ± 20 W; Figure 2). In fact, CP is conceptually equivalent to MLSS (Keir et al. 2018a; Mattioni Maturana et al. 2016) although empirically CP often occurs at a higher power output than MLSS (Jones et al. 2019). Nevertheless, the close agreement between the calculated CP and the lactate measured MLSS power output gives confidence into the correctness of our data collection. However, while CP and the power output at MLSS agreed, the TTE's at this similar power output were different. They were 4:41 min longer when calculated by CP and W'. As it is shown in Figure 3, the mathematical constrains of fitting data into a hyperbole with the CP calculation, resulted in a lower nadir than with the measured data. This probably led to lower asymptotes in both sides of the hyperbole, explaining the overestimation of TTE at MLSS and $WAnT_{mean}$ when using CP and W'.

$TTE_{measured}$ at MLSS workload (i.e., 247 ± 20 W) is to our knowledge, the highest in the literature (i.e., 76:05 ± 13:53 mm:ss). For instance, Baron et al., (Baron et al. 2008) using elite cyclists reported 55:00 ± 08:30 mm:ss for TTE at MLSS. Several factors could explain our longer endurance at similar power-output. We allowed subjects to freely choose cycling cadence which optimizes metabolic efficiency (Barker et al. 2006; Hill et al. 1995) by increasing cadence with increasing power output (Table 2; (Sidossis et al. 1992)). Secondly, cyclists used their own bicycles and were not limited by cycle-ergometer geometry, and lastly we allowed water rehydration *ad libitum*. Rehydration prevents cardiovascular drift and overly increases core temperature and muscle glycogen use (Fernandez-Elias et al. 2015). These factors could explain why our cyclists were able to extend TTE at MLSS power output beyond published reports with lower intra-subject variability (CV 5% vs. 25% (Faude et al. 2017)).

Time to exhaustion at CP is generally less than 60 min (Housh et al. 1989) which is the minimal duration expected to be held at MLSS workload (Jones et al. 2019). Indeed, Mattioni Maturana and co-workers (Mattioni Maturana et al. 2016) and more recently Jones et al.,(Jones et al. 2019) suggest that CP overestimated maximal lactate steady state (MLSS) by approximately 8%. This has led some authors to propose that CP may be similar to a physiological threshold of higher power output namely, the respiratory compensation point (RCP or VT_2; (Dekerle et al. 2003)). However, we have recently reported in trained cyclists and runners, that the workload that elicits MLSS is located below VT_2 (Cerezuela-Espejo et al. 2018; Pallares et al. 2016) and presently that CP is also below VT_2 workload (Figure 2). Furthermore, $TTE_{measured}$ at the power output of VT_2 (302 ± 31 W) is around 11:29 mm:ss. In contrast, the CP derived TTE at this intensity was only 7:11 m:ss (i.e., 34% difference). Given that modern training heavily targets exercise intensities in the neighborhood of VT_2 (Coyle et al. 1991; Esteve-Lanao et al. 2007; Seiler 2010; Seiler and Sjursen 2004) the underestimation incurred by CP derived TTE could result in stagnation of training adaptations. Our $TTE_{measured}$ at VT_2 (i.e., 11:29 m:ss) is similar to what Bergstrom et al., (Bergstrom et al. 2012) reported in 8 moderately-trained subjects (i.e., 11:12 ± 03:06 mm:ss). Thus, $TTE_{calculated}$ of 7:11 m:ss is most likely an underestimation of real TTE at VT_2 power-output.

We found that CP calculated TTE at the workload that elicits VO_{2max} using 25 $W \cdot min^{-1}$ graded exercise testing, (366 ± 26 W) coincided with the real measures (3:23 vs. 3:15 mm:ss, $P = 0.493$; Figure 3). Thus, our data suggest that in this case, CP is a reliable estimator of TTE at the power output that elicits VO_{2max} using a 25 $W \cdot min^{-1}$ incremental protocol. Perhaps, the TTE at the power at VO_2max is the most studied time to exhaustion to date. TTE seems to be affected by the type of locomotion or by the incremental protocol used to identify the workload that elicits VO_2max (i.e., short incremental vs several longer constant workloads). Following a common methodology, Billat et al., (Billat et al. 1996) reported TTE values of 03:42 ± 01:31, 06:16 ± 02:14, 04:47 ± 02:40 and 05:21 ± 01:24 mm:ss, for cyclists, kayakers, swimmers and runners, respectively. In addition Faina and co-workers (Faina et al. 1997) reported TTE of 03:45 ± 01:34, 05:56 ± 01:25 and 05:02±02:16 mm:ss with cyclists, kayakers and swimmers, respectively. Our data in cyclists coincides with these reports on TTE at VO_2max power output between 03:30 - 03:45 mm:ss in cyclists. However, the reasons for the differences in TTE at VO_2max power output between types of locomotion, and the CP capacity to predict TTE in each mode are uncertain.

CP estimate of TTE at the highest power (i.e., WAnTmean) grossly overestimated cyclists' capacity to maintain that power output (i.e., 710 ± 63 W) from 29 to 52 seconds (86% overestimation). Power training cycling sprints at WAnT workloads (710 ± 63 W) based on $TTE_{calculated}$ will be too demanding (by almost 1-fold in time) which will drive cyclists to premature exhaustion increasing the risk of overtraining or injury. One recent study suggests that the 2-parameter hyperbolic fitting may overestimate TTE in performances below 2 min in comparison to the 3-parameter fitting (Vinetti et al. 2019). In that study, healthy-moderately active subjects were able to cycle against 562 W for 24 seconds allowing authors to extend CP to durations below

2 min. Our results using trained cyclists able to maintain 710 W for 29 seconds coincide with the overestimation of TTE calculated with CP and W' suggesting, that critical power predictions should not be used to calculate TTE during power training cycling sprints.

Our study is not free of limitations. The power output at the different physiological thresholds (i.e., WAnT, VO_2max, VT_2 and MLSS) was derived from a graded cycling exercise test conducted using 25 W·min^{-1} stages. Thus, those power output pertain only to that testing protocol and would vary if stages intensity and/or duration differ from what it is presented (Iannetta et al. 2019b). Although we do not present the relationship between power output and VO_2, this would also be affected by the incremental test we used since it does not account for the upward drift in VO_2 at power-outputs above the gas exchange threshold (VT_1). Further since we average VO_2 during the last 15 sec of each minute stage, we did not account for the changing mean response time of VO_2 with increasing stage intensity (Iannetta et al. 2019a). Thus, it will be wrong to deliver a universal training advice on those thresholds based on absolute (e.g., 300 watts at VT_2) or relative workloads (e.g., VT_2 at 85% of VO_2max; (Iannetta et al. 2019c)). Despite these limitations, our data remain valid on the main objective of the study which is to test the accuracy of CP to predict time to exhaustion (TTE) at common cycling training power-outputs (i.e., 200 – 800 W).

Fitting power output vs. duration data to a hyperbole and calculating the asymptote (i.e., critical power; CP) allows estimation of time to exhaustion (TTE) in a wide range of exercise intensities. Thus, the use of CP is very attractive to coaches since it could improve their training prescription, incorporating science-based duration advice at each exercise intensity. However, CP estimations of TTE are based on 3-5 exercise bouts at exercise intensities that elicit exhaustion between 2-15 min, leaving untested exercise intensities that are common training targets (i.e., intensity at MLSS or at power outputs above those eliciting VO_2max). This constrains the obtained hyperbole to a short range of data points with the result of lowering the nadir and extending the asymptotes (Figure 3).

To our knowledge, this is the first study that compares the results of TTE estimated by CP with real TTE in those untested but important power-outputs (i.e., intensities that induce exhaustion below 2 min and above 15 min) in cyclist. We found that TTE estimated by CP is appropriate when prescribing training durations at the power output that elicits VO_2max measured by using a 25 $W \cdot min^{-1}$ graded exercise testing. However, it overestimates TTE at MLSS and $WAnT_{mean}$ and largely underestimates TTE at the power output that elicit VT_2 when measured by using a 25 $W \cdot min^{-1}$ graded exercise testing. Incorrect TTE calculation with CP, would result in prescribing exercise training bouts either too short to elicit training adaptations, or too long and demanding leading to early exhaustion and overtraining. In summary, cycling coaches should use CP cautiously. Real individual TTE measurement seems unavoidable at high and low power-outputs to provide correct coaching advice.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to report.

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FIGURE CAPTIONS

Figure 1. Study design.

Figure 2. Power output during the 4 constant-power trials including the calculated power output at critical power (CP). Data in the box represents median and quartiles with whiskers representing the range of data. Data for 14 endurance-trained cyclists.

Figure 3. Time to exhaustion (TTE) – power output relationship. Data are mean ± SD of the 4 constant-power trials for 14 endurance-trained cyclists when measured or calculated using critical power (CP) 2-parameter formula (i.e., $TTE_{calculated}$ = W' / (W – CP)).

Table 1. Anthropometric and fitness charateristics.

	Age (y)	Height (cm)	Weight (kg)	VO_2max (L/min)	VO_2max (mL/kg/min)	PO_{peak} (W)	Train (y)
Mean	34.7±9.1	176.2±7.3	73.0±9.4	4.19±0.38	57.9±5.4	377±26	5±1
Range	(22.2-46.8)	(167.0-190.0)	(58.6-92.8)	(3.52-4.75)	(47.3-64.5)	(335-432)	(3-8)

Data are presented as mean±SD and range for 14 endurance-trained cyclists.

Table 2. Physiological data obtained at the 4 contant power trials.

	PO (W)	Tlim (mm:ss)	RPE_{peak} (6-20)	HR_{peak} ($bt \cdot min^{-1}$)	$[Lac]_{peak}$ (mM)
WAnT	710±63	0:28±0:07	20.0±0.0	174±11*	9.0±3.0
VO_2max	366±26	3:23±0:39	19.4±0.4	180±14	11.5±4.2
VT_2	302±31	11:24±5:00	19.1±0.7	176±08*	12.1±2.8
MLSS	247±20	74:06±13:30	17.9±1.3*	164±11*	4.9±2.3*

Data are presented as mean±SD for 14 endurance-trained cyclists. CBL stands for capillary blood lactate, PO stands for power-output. PO_{peak} is the power at which VO_2max is achieved. *Significantly different from the VO_2max trial in RPE, HR_{peak} and $[Lac]_{peak}$.

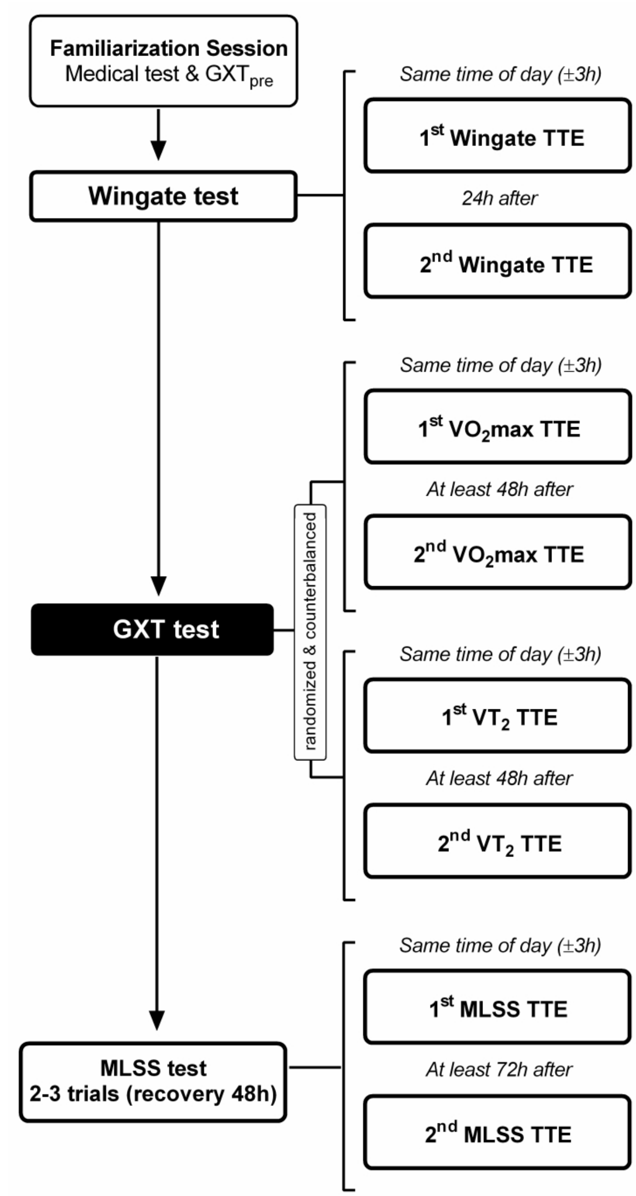

Figure 1. Study design

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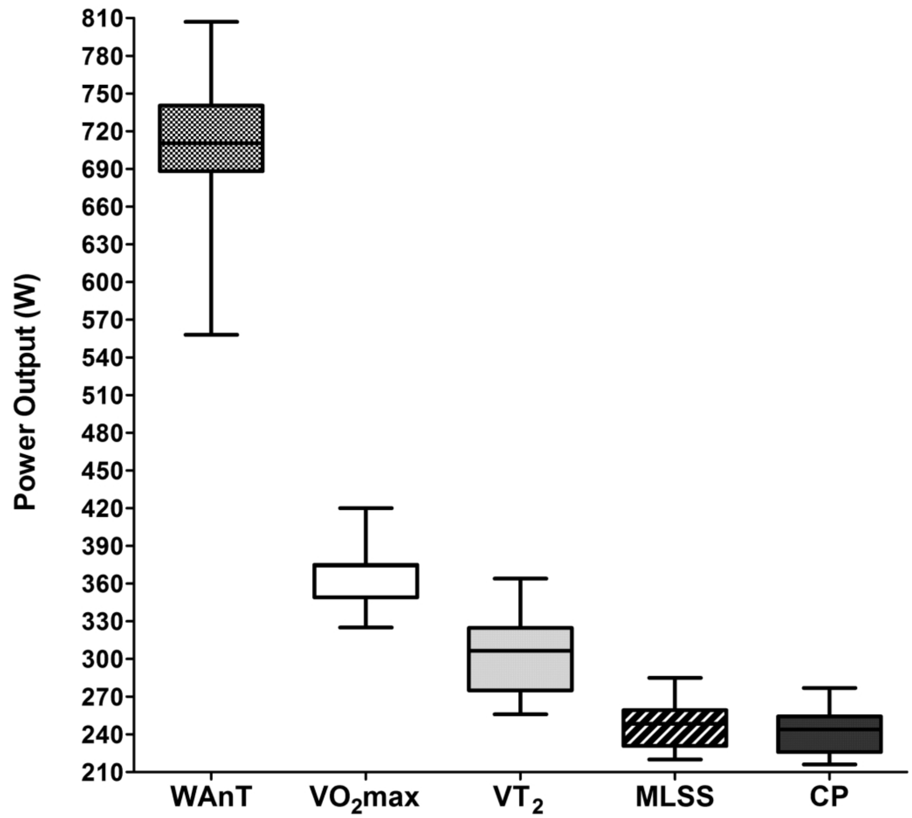

Figure 2. Power output during the 4 constant-power trials including the calculated power output at critical power (CP). Data in the box represents median and quartiles with whiskers representing the range of data. Data for 14 endurance-trained cyclists.

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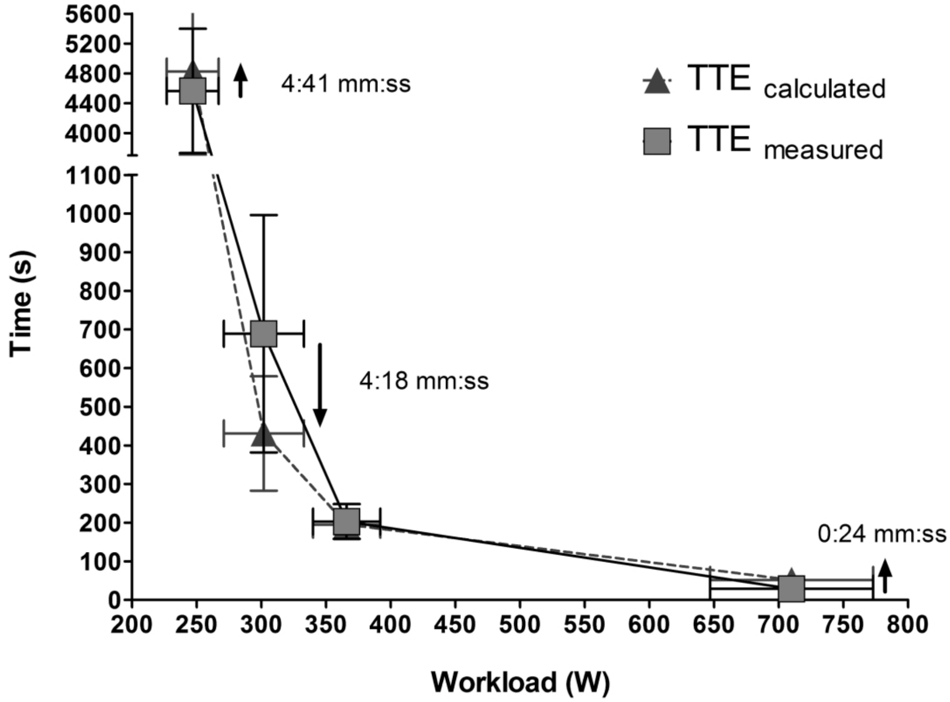

Figure 3. Time to exhaustion (TTE) – power output relationship. Data are mean ± SD of the 4 constant-power trials for 14 endurance-trained cyclists when measured or calculated using critical power (CP) 2-parameter formula (i.e., TTEcalculated = W' / (W – CP)).

194x145mm (300 x 300 DPI)