ORIGINAL ARTICLE

T10 Test as an Alternative Method to Assess Critical Speed and its Potential Application to Runners

Edilson Fernando de Borba[1] · Lucio Follador[1] · Sara Crosatti Barbosa[1] · Marcus Peikriszwili Tartaruga[1] · Sergio Gregorio da Silva[1]

Abstract

Exercise intensity is usually prescribed based on a metabolic marker, such as maximum oxygen uptake or maximal lactate steady state. Those markers, however, face some difficulties regarding their practical applicability to the general population. The critical speed emerges as an alternative parameter to determine aerobic exercise intensities through maximal tests using ergometers or field tests, demanding few resources. We evaluated the fidelity of test to predict critical speed and if this parameter could be used to prescribe intensity in aerobic exercise. One hundred recreational runners performed the T10 test and a conventional critical speed test to define running speeds. Out of them, 44 runners proceed continuous and interval races. The critical speed assessed from T10 test was then compared to critical speed measured by three maximal runs in the track field (1200 m, 2400 m, and 3600 m). We found a strong correlation ($r = 0.91$) and did not find statistical differences ($t = 1.8$, $P = 0.90$) between critical speed assessed by T10 (3.89 ± 0.49 m/s) and field-test (3.85 ± 0.51 m/s). T10 is also better associated with running and interval running speeds than metabolic markers. T10 test can be used as a valid alternative method to assess critical speed and to prescribe runs.

Keywords Critical velocity · Exercise intensity domains · Race · Running · Interval aerobic training

Abbreviations

VO_{2max}	Maximum oxygen uptake
HRmax	Maximum heart rate
GET	Gas exchange threshold
LL	Blood lactate
T10	10-Min treadmill test
VT	Ventilatory threshold
CS	Critical speed
CP	Critical power
VT_2	Second ventilatory threshold

Introduction

Exercise intensity is determinant to physiological responses to training [39]. Intensity is usually prescribed based on maximum heart rate (HRmax), maximum oxygen uptake (VO_{2max}), gas exchange threshold (GET), or blood lactate (LL) [13]. The anaerobic threshold can be determined through LL [19] or ventilatory threshold (VT) measured in a maximal exercise testing [1] until then considered gold standard to define exercise intensity [25]. We previously used the GET to demarcate the boundaries between the moderate and heavy intensities and the second ventilatory threshold (VT_2) to set the limits between heavy and severe intensities [11]. Identifying intensity boundaries is essential to prescribe interval and continuous exercise, and the limits between heavy and severe are crucial to set up intensity zones when exercise tolerance can be easily changed. However, prescribing intensity can be complex. There are controversies about the reliability and validity of methods [23], and most of those do not consider cardiorespiratory levels of individuals.

Moreover, they are not very accessible for the general population. Critical speed (CS), or critical power (CP), is defined as the highest sustained speed/power without exhaustion, because it is a parameter that represents the maximum respiratory and metabolic steady state [38], it can be used as a viable alternative to prescribe intensity in continuous and interval aerobic exercise [28].

✉ Edilson Fernando de Borba
borba.edi@gmail.com

1   Postgraduate Program in Physical Education, Federal
     University of Paraná, Curitiba, Brazil

The CS demarcates the boundary between the heavy and severe intensity domains [16]. It is also associated with other aerobic fitness parameters, such as GET, VO_{2max} [21, 31, 32], and the performance in prolonged endurance exercises [12]. Previous work tested the CS in a single test [35], however, it is a maximum test, and our intention is to reduce the workload in the test so that athletes can perform in several opportunities throughout the periodization. This relation between CS and some physiological exercise indicators supports that CS can prescribe and control exercise intensity in continuous and interval aerobic training in the sedentary, clinical or athletic population. Once CS can predict athletic performance, then it can be helpful for endurance training programs [38].

The determination of CS is a cost–benefit and relatively easy application strategy. There are, however, some significant limitations with those conventional methods [17, 24], turning into physically and mentally exhausting tasks, demanding maximal effort in numerous running tests [9]. Recently an alternative was proposed to estimate CS in one single running submaximal test [14], reducing mental and physical efforts, the T10 can be performed in different phases of training, without worrying about the high wear of a maximum test, whether it is a single maximum run or multiple runs. The test consists of a 10-min treadmill run at a self-selected velocity (T10). This new proposed model may be a valid alternative for determining the CS in 5, 10, 21, and 42 km runners. To our knowledge, no study has verified whether T10 can estimate CS in 5, 10, 21 and 42 km runners. Concomitantly, analyzing in which intensity domains the runners are practicing continuous and interval runs based on the result of the CS of this new model can be a way to direct training, facilitating access for the population that practices running as a sport modality.

Therefore, the objective of the present study was to verify if the T10 can estimate the CS in 5, 10, 21 and 42 km runners. Another aim was to describe the speeds that individuals train based on the CS. The hypotheses are that the T10 will respond similarly to the traditional methods (maximal tests) for 5, 10, 21, and 42 km runners. Also, interval training speeds will be above CS while continuous ones will be below.

Methods

Participants

The sample was composed of 100 recreational runners (77 males and 23 females), with age between 18 and 49 years (34.36 ± 7.2) (body mass: 70.71 ± 8.76 kg, BMI: 23.51 ± 2.19 kg/m^2) and with at least 2-year running experience. As inclusion criteria, participants had to prove aerobic fitness by running at least one of these distances: 5, 10, 21 and 42 km. Men should complete 5 and 10 km under 25 and 55 min, respectively, while women should complete it under 35 and 65 min. Regarding the 21 and 42 km, both sexes should complete the runs under 120 and 240 min, respectively. Race times were defined based on data from recreational runners [41]. All participants presenting any disease or injury that could influence the running results were excluded. This study was approved by the local Ethics Committee in compliance with the Declaration of Helsinki, and written informed consent was obtained from all participants.

Experimental Design

In this cross-sectional study, participants were subjected to a battery of laboratory and field running tests to determine aerobic capacity, CS, to set the interval and continuous running speeds and their associated intensity domains (Fig. 1). Tests were conducted within at least 24 h apart, we chose this recovery period for those who had no influence of fatigue on the results, and all subjects agreed not to exercise in hard intensities within the 24 h before the tests.

Fig. 1 Experimental Design. VO_{2max}: maximum oxygen uptake; vVO_{2max}: velocity associated with VO_{2max}; T10: 10-min treadmill test
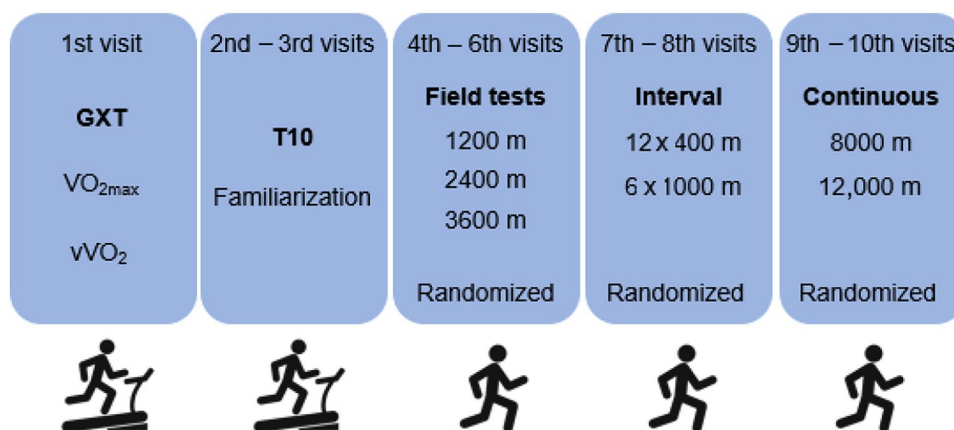
As fatigue control, we used the subjective feedback of each individual, where the individual should report being completely recovered to perform the task. This feedback was given by responding to the evaluator if the individual considered himself/herself able to perform the test, in this case without being fatigued to the point of compromising performance. This response was used based on the Subjective Perception of Recovery scale [33]. The tests were performed simultaneously, and the participant defined the choice of time. Subjects visited the laboratory on three occasions. In the first visit, participants were subjected to a graded exercise test to determine aerobic fitness. In the second one, they performed the T10 test to get familiar with it, and finally, in the last visit, they performed the T10 test officially. In the three subsequent visits, participants performed field tests (1200, 2400, and 3600 m) to set CS. Tests occurred in a 400 m track field. In the next two subsequent visits, participants performed interval runs in the track field (6×1000 m and 12×400 m), and in the last two visits, they performed long continuous endurance runs (8000 and 12,000 m). Thus, every subject performed ten physical tests.

Maximum Graded Exercise Test To The Determination of VO_{2max}, GET and VT_2

The graded exercise test was performed on a treadmill (Master Super ATL, Inbramed, Brazil) with portable equipment for measuring respiratory exchange gases, calibrated according to manufacturer's recommendations (K4b^2 COSMED, Rome, Italy) to determine VO_{2max}, velocity associated with VO_{2max}, GET, VT_2 and HRmax. The test began at 8 km/h for 5 min, and the speed was raised 1 km/h every minute until participants reached exhaustion. The treadmill was inclined by 1% to simulate outdoor running [26]. Heart rate (HR) was monitored (H10, Polar Electro Oy, Kempele, Finland) during the whole test. VO_{2max} was determined by the highest VO_2 value during the last 30 s of the test. The test was ended when the subject reached at least two out of three criteria [10], which are: (1) to show oxygen uptake plateau, when VO_2 did not increase with increasing running speed (2) reach a respiratory exchange ratio greater than 1.2 and (3) to exceed 90% HRmax predict from age ($208 - 0.7 \times$ age). Velocity associated with VO_2 was determined as the minimal speed at which the participant attained VO_{2max} as long as the speed was maintained for a full minute [3]. The ventilatory thresholds were determined through V-Slope analysis by the equipment's native software (K4b.^{2}), the method is described by Beaver et al. [1]

10-Min Submaximal Treadmill Test

The first T10 test was carried out to become familiar with the equipment, and the second test was to determine CS. Before the T10 test, participants were given this instruction: "Pick a vigorous velocity that you can keep for the next 10 min. You can change it during the first 5 min but must keep a constant speed in the last 5 min. You will be warned about how much time left in the minute 4 min 30 s, 4 min 40 s, and 4 min 50 s, during the first 5 min". This instruction was accessible to the participant during the whole test. The test was initiated at speed 1.1 m/s, and participants were allowed to change speed, and each click on the speed control panel up or down changed the speed by 0.03 m/s. Treadmill display was covered to prevent participants from checking the speed, distance, and time, more details of the protocol can be found in the article by Follador et al. [14, 15]. Respiratory gas exchange was monitored breath-by-breath (K4b^2 COSMED, Rome, Italy). The speed of the last 5 min was defined as the critical speed. If the athlete could not finish the test at that speed, the test was repeated at another opportunity. All participants completed the test without the need to interrupt or slow down the treadmill.

Critical Speed Field Test

In 3 different days (minimal 24 h interval), participants performed tests on a running track (400 m) to determine the CS. They were instructed to run the proposed distances (1200 m, 2400 m, and 3600 m) quickly. The runs were performed randomly, and the participants only knew these distances moments before the tests. All participants were advised to take the tests only if they were feeling completely recovered. Run times were recorded using a digital stopwatch using iPhone X (Apple Inc, Califórnia, USA), and CS was determined by linear regression of distance x time [20].

Interval and Continuous Running

To verify and present the running speeds and relate the speeds to the intensity domains based on the T10 speed, a subgroup of 44 participants performed the interval and continuous runs. Interval running was conducted in the track field (400 m) on different days (minimal 24 h interval). Participants only knew the distance right before the test. In one of the visits, they were instructed to perform 12 bouts of 400 m, with 1 min 30 s passive rest between bouts. In another visit, they performed 6 bouts of 1000 m, with 3 min passive rest between bouts. Therefore, intensity should be considered *hard,* and both running tests should present similar times. In the last two visits, participants performed continuous endurance running in a city park, flat and well-paved, with demarcations every 100 m. Runs were performed randomly, in 2 days, with one hard-intensity 8000 m endurance running and one moderate-intensity 12,000 m endurance running. Again, all participants were advised to take the tests only if they were feeling completely recovered

for realize the run. The distances were chosen based on the authors' practical experience. Running times were registered using an iPhone X digital chronometer (Apple Inc, Califórnia, USA).

Statistics Analysis

The distribution of the data was analyzed by the Shapiro–Wilk test. Velocities collected by T10 and field tests (1200 m, 2400 m, 3600 m) were compared using Student's T-test. Bland–Altman plots were used to assess agreement between the velocity in T10 and CS determined by field test. Lin's concordance correlation coefficient was applied to determine the reliability of methods, following the criteria: $RC = 0.21$–0.40 reasonable; 0.41–0.60 moderate; 0.61–0.80 substantial e 0.81–1.00 almost perfect [30]. This Lin's statistic test allows measure, numerically and graphically, the concordance and the reliability of two different methods by comparing repeated measures. We used Pearson's correlation coefficient to analyze the correlation between velocities collected by T10 test and field tests (1200 m, 2400 m, 3600 m), and the interpretation was based following these criteria: $r < 0.3$ negligible; 0.3–0.5 weak; 0.5–0.7 moderate; 0.7–0.9 strong; > 0.9 very strong. To analyze differences between velocities applied to each running distance tested interval and continuous runs, we used one-way repeated measures ANOVA. The comparison between differences was expressed using Cohen's d (effect size), with a CI of 95%. The magnitude of differences was interpreted as trivial (0–0.19), small (0.20–0.49), medium (0.50–0.79), and large (≥ 0.80) [8] as alternative significance metrics [43]. Statistical analysis was performed using SPSS (version 25.0; SPSS, Inc., Chicago, IL, USA) with a significance at 5%.

Results

CS Protocols Analysis

The VO_{2max}, T10 speed test and CS measured by field test of the participants were respectively, 52.05 ± 6.09 mL/kg/min, 3.89 ± 0.49 m/s, and 3.85 ± 0.51 m/s. There was no difference between T10 and the field test ($P = 0.90$).

Figure 2 shows the VO_2 profile (in 15 s intervals) during the T10 test. VO_2 rapidly raised in the first 180 s during the test, then it turned into a modest raising right after the 180 s and reached a steady-state-like around 420 s. During the last 5 min of the T10 retest, the speed was above the velocity associated with GET but below the velocity associated with VO_{2max}.

Figure 3 shows the relation the bias $\pm 95\%$ limits of agreement between the speed of the T10 test and the CS estimated from the field test (0.04 ± 0.43 m/s, CI $95\% = -0.46$–0.39). Standard error (SE) was 0.16 m/s while correlation coefficient between T10 test and CS field test was $r = 0.91$ (CI $95\% = 0.86$–0.94). Regression analysis resulted in the following predictive equation: $y = 0.875x + 0.25$, R^2 adjusted of 0.82.

Figure 4 shows Lin's concordance correlation coefficient ($RC = 0.90$, CI 95%: 0.93–0.86) and correction factor (CB: 0.99).

Speed Analysis

After determining CS through the T10 test, 44 participants of the whole sample were invited to perform 2 interval and 2 continuous run protocol. The VO_2 data and thresholds of this group were: VO_{2max} 53.38 ± 6.46 mL/kg/min, GET

Fig. 2 VO_{2max} profile during T10 test. VO_2 remains slightly under GET during the first phase of the test (300 s), and then it raises to get steady between GET and VO_{2max} threshold
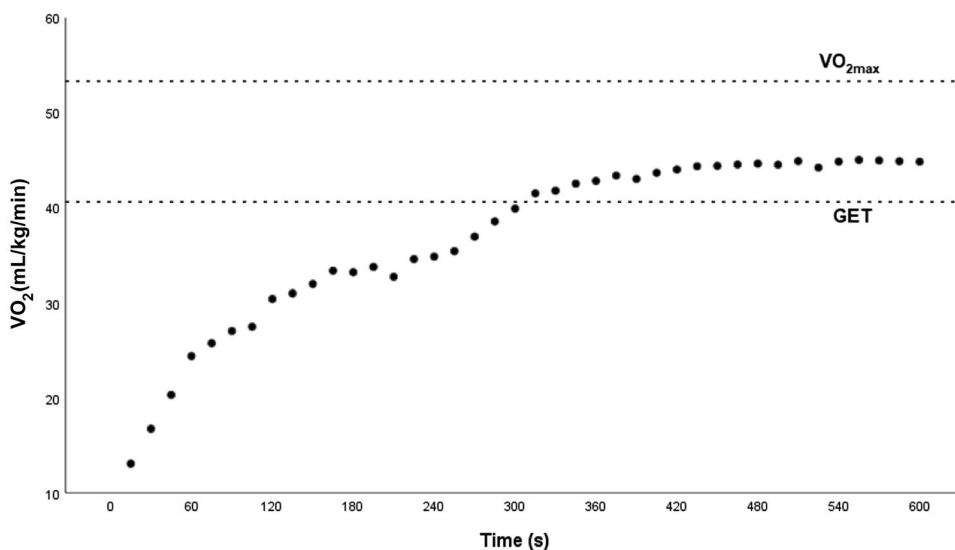
Fig. 3 - Bland–Altman plot of limits of agreement between field test estimated CS and T10 test speed. The solid horizontal line represents the mean difference between field test estimated CS and T10 test speed, and dashed lines represent the 95% limits of agreement
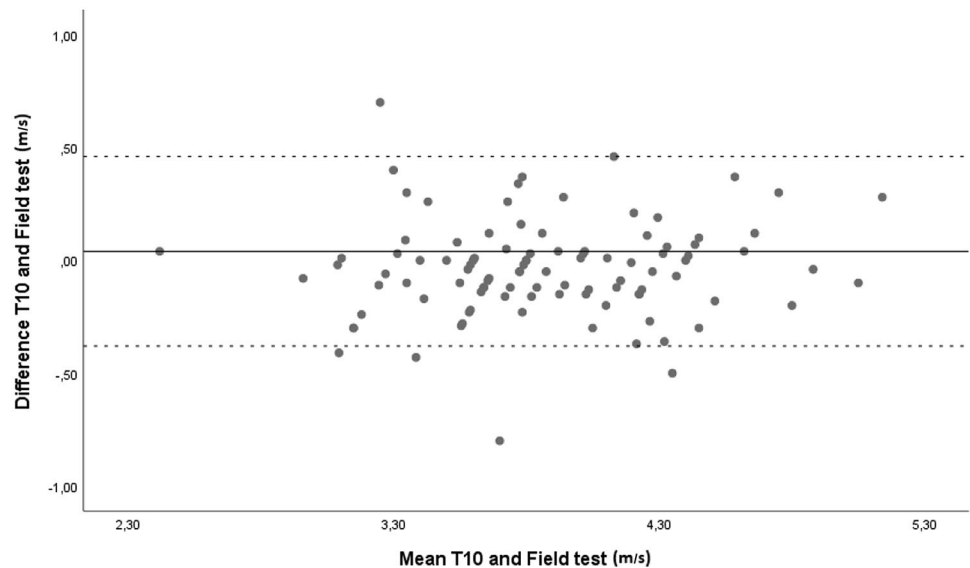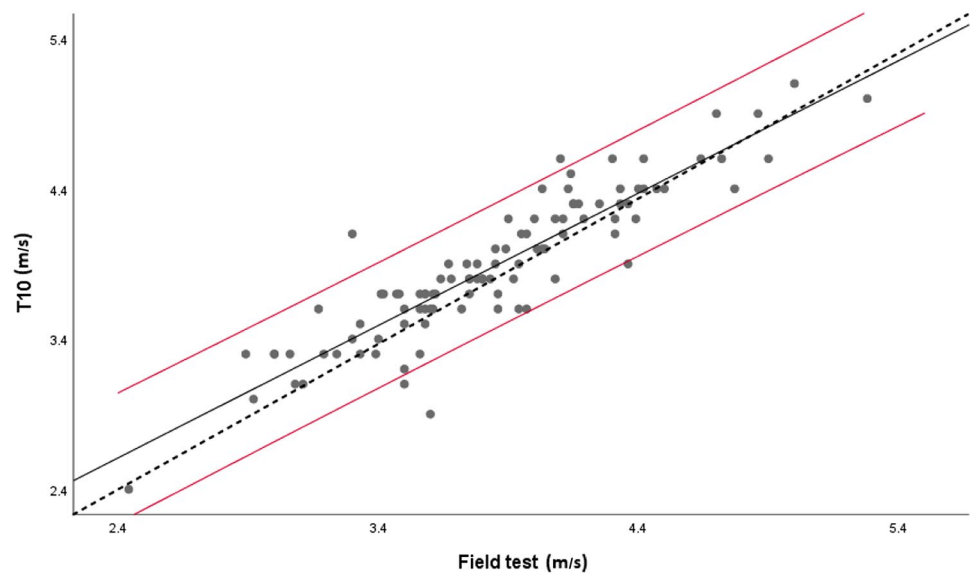

Fig. 4 Lin's method analyzes the agreement between T10 and field tests. The solid line is the linear regression's best adjustment, the dashed line is the identity line, and the external lines demarcate the confidence interval (95%)

40.68 ± 6.22 mL/kg/min, VT_2 47.34 ± 6.02 mL/kg/min and T10 test at 44.62 ± 6.22 mL/kg/min.

The one-way repeated measures ANOVA showed that the mean speed in each run is affected by the selected distance [F (2.53, 108.72) $= 383.77$; $P < 0.001$]. The differences between velocities were expressed as Cohen's d effect size, with 95% CI, reporting that all runs had significantly different speeds. The interval runs were performed at 4.54 ± 0.62 m/s and 4.15 ± 0.56 m/s for 400 and 1000 m, respectively, and the continuous runs were performed at 3.79 ± 0.50 m/s and 3.32 ± 0.39 m/s for 8000 e 12,000 m, respectively (Fig. 5).

Both 400 m and 1000 m interval running are mean speed performed above the speed measured by T10 test ($119.82\% \pm 5.03\%$ and $109.77\% \pm 3.29\%$, respectively), while the 8000 running's speed was similar to T10 ($99.63\% \pm 2.85\%$) and the 12,000 running's speed was performed below, reaching $87.32\% \pm 4.25\%$ from speed measured by T10 test, the difference between the speeds is described in Table 1.

The Person's Correlation Coefficient analysis reported a significant correlation between the T10 test and the energetic parameters speeds (vVO_{2max}, vGET, and vVT_2) in the interval and continuous running. However, the strongest correlation was found with running's speed, either in the interval and continuous running (Table 2).

Fig. 5 Interval and continuous participants' speeds. VO_{2max}: maximum oxygen uptake; VT_2: second ventilatory threshold; T10: mean CS measured by T10 test; GET: first ventilatory threshold
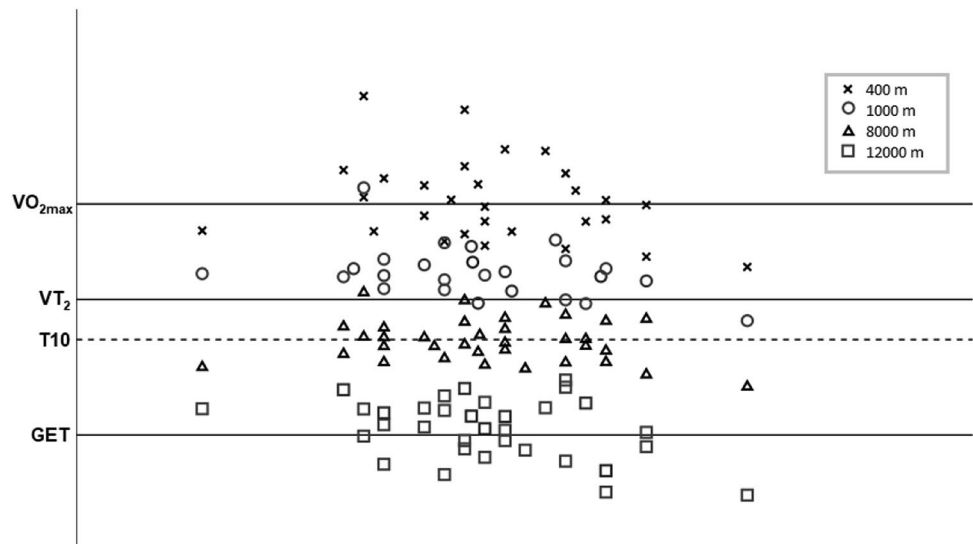

Table 1 Speed expressed as mean $\pm$ SD (m/s) of energetic parameters and interval and continuous running. Mean differences are described as Cohen's d effect size (95% CI)

Speed	12×400 m 4.54 ± 0.62	6×1000 m	8000 m	12,000 m	T10
6×1000 m 4.15 ± 0.56	0.67 (0.24, 1.10) $P < 0.001$				
8000 m 3.79 ± 0.50	1.34 (0.87, 1.80) $P < 0.001$	0.66 (0.23, 1.09) $P < 0.001$			
12,000 m 3.32 ± 0.39	2.36 (1.81, 2.90) $P < 0.001$	1.7 (1.21, 2.19) $P < 0.001$	1.03 (0.58, 1.47) $P < 0.001$		
T10 3.81 ± 0.49	1.31 (0.85, 1.78) $P < 0.001$	0.65 (0.22, 1.08) $P < 0.001$	0.04 (− 0.39, 0.46) $P = 0.3$	1.06 (0.61, 1.51) $P < 0.001$	
vGET 3.48 ± 0.62	1.92 (1.41, 2.43) $P < 0.001$	1.26 (0.80, 1.71) $P < 0.001$	0.63 (0.20, 1.06) $P < 0.001$	0.32 (− 0.11, 0.74) $P = 0.04$	0.7 (0.26, 1.13) $P < 0.001$
vVT_2 4.07 ± 0.52	0.84 (0.40, 1.28) $P < 0.001$	0.15 (− 0.27, 0.57) $P = 0.2$	0.56 (0.13, 0.98) $P < 0.001$	1.63 (1.15, 2.11) $P < 0.001$	0.52 (0.09, 0.94) $P < 0.001$
vVO_{2max} 4.58 ± 0.55	0.07 (− 0.35, 0.49) $P = 0.5$	0.8 (0.37, 1.24) $P < 0.001$	1.52 (1.05, 1.99) $P < 0.001$	2.65 (2.08, 3.23) $P < 0.001$	1.48 (1.01, 1.95) $P < 0.001$

Discussion

The present study showed that the T10 test could predict the CS with similar results compared with conventional methods (Figs. 3 and 4). These results suggest that T10 represents an alternative to identify the speed associated with the maximum metabolic steady-state and can be used as a parameter to control continuous and interval runs (Fig. 5).

Our study found no significant difference ($t = 1.8$, $P = 0.90$) between the speeds measured with the T10 test (3.89 ± 0.49 m/s) and those measured with field test (3.85 ± 0.51 m/s), with a mean difference of 0.04 m/s (SEE of 0.16 m/s). Besides, we found a strong correlation ($r = 0.91$) and low risk of bias between those different methods. In this way, CS measured by the T10 test is an alternative to demarcate the boundary between hard and severe intensity domains. There is a growing interest in investigate

Table 2 Correlation coefficients (95% CI) between T10 speed, performance during the interval and continuous running, and the speed associated with energetic parameters

Parameters	vVO_{2max}	vGET	vVT_2	T10
12×400 m	0.82	0.63	0.74	0.94
	(0.69–0.90)	(0.39–0.78)	(0.57–0.85)	(0.89–0.97)
6×1000 m	0.79	0.59	0.71	0.93
	(0.65–0.88)	(0.35–0.76)	(0.53–0.83)	(0.88–0.96)
8000 m	0.83	0.64	0.75	0.96
	(0.71–0.90)	(0.41–0.79)	(0.58–0.86)	(0.93–0.98)
12,000 m	0.79	0.58	0.69	0.92
	(0.64–0.88)	(0.34–0.75)	(0.50–0.82)	(0.85–0.96)

vVO_{2max} speed associated with maximum oxygen uptake, *vGET* speed associated to gas exchange threshold, *vVT_2* speed associated to the second ventilatory threshold, *T10* speed associated to T10 test.

All observations with $P < 0.001$

the validity of using CS to predict aerobic performance [5, 7, 22, 25, 34]. Some studies report that CS measured by field tests (distance vs. time) is similar and highly correlated to the CS predicted by treadmill test, such as the study of [29] that found a strong correlation ($r = 0.9$) between CS predict by treadmill and field tests in highly trained 10 km runners. [14] shows similar results ($r = 0.93$; 90% CI: 0.88–0.96) comparing T10 and field tests performed by recreational runners. Using Lin's concordance correlation coefficient, which determines if two different methods can predict the same outcome [30], showed that the T10 test could predict CS with high precision ($RC = 0.90$).

The T10 test showed a higher association with running performance, either interval or continuous run, than those related to other different metabolic markers (vVO_{2max}, vGET e vVT_2). Based on Pearson's correlation tests and Cohen's effect size, presented in Tables 1 and 2, we believe that the use of this method may be more sensitive to changes in the individual's performance, similar data were found in Follador et al. [15] using T10 as a performance predictor for 5 and 10 km races. These correlations are used in other articles to describe the association between VO_{2max}, VO_{2peak} and running [4]. There is no significant difference between the speed measured by the T10 test and the mean speed to run 8000 m. Also, the mean time to perform this run was nearly 35 min, similar to studies that determinates that exhaustion will happen up to 60 min in a continuous running at CS [2, 20]. The speed in 400 m and 1000 m runs was performed above the speed measured by T10, suggesting that both were positioned in the severe domain of intensity.

Poole et al. [36], published the first study to evaluate the homeostatic response above the CS, predicted by the conventional method and confirmed the validity of CS to demarcate the boundary between the hard and severe

domains. Those results were confirmed or replicated in several other studies [6, 18, 40]. Recently, one study [25] presented the CS as the best indicator to limit the hard and severe intensity domain in exercise. Therefore, CS is an appropriate metrics when the objective is to evaluate the maximum metabolic steady-state [5]. Beyond the applicability in continuous endurance runs, some authors suggest that CS could be applied to interval running, too [27]. In this case, we could use T10 as an alternative to prescribe and control interval and continuous running because, based on the hypothesis that the self-selected speed during the T10 test would be close to a metabolic steady-state [37, 42], we can report that the test can successfully determinate the limit between hard and severe intensity domains. Thus, we can affirm that interval runs, performed above the speed measured by T10, were performed in the severe domain of intensity while the continuous runs, where participants ran at or below the T10 test speed, were in the hard or moderate-intensity domain.

Conclusion

Our findings prove the reliability of the T10 test to predict CS and could be adopted as an alternative to conventional methods. Results also showed that the T10 test was associated with speeds in the interval and continuous runs. This association was higher than those found with the running and other performance markers (GET, VT_2, VO_{2max}), reinforcing the feasibility of using T10 to prescribe aerobic training. These results provide evidence about the validity and potential practical application of T10 to define interval and continuous runs, due to its ability to set the limits between the hard and severe domains of exercise intensity.

Declarations

Conflict of Interest The authors declare that they have no conflicts of interest regarding the publication of this paper.

Consent to Participate All participants reviewed and signed informed consents before participating in the study.

Consent for Publication All participants reviewed and signed informed consents that their data be published anonymously.

References

1. Beaver WL, Wasserman K, Whipp BJ. A new method for detecting anaerobic threshold by gas exchange. J Appl Physiol. 1986;60(6):2020–7. https://doi.org/10.1152/jappl.1986.60.6.2020.

2. Bergstrom HC, Housh TJ, Zuniga JM, Traylor DA, Lewis RW, Camic CL, Schmidt RJ, Johnson GO. Responses during exhaustive exercise at critical power determined from the 3-min all-out test. J Sports Sci. 2013;31:537–45. https://doi.org/10.1080/02640414.2012.738925.

3. Billat VL, Flechet B, Petit B, Muriaux G, Koralsztein JP. Interval training at VO_{2max}: effects on aerobic performance and overtraining markers. Med Sci Sports Exerc. 1999;31(1):156–63.

4. Billat V, Lepretre PM, Heugas AM, Laurence MH, Salim D, Koralsztein JP. Training and bioenergetic characteristics in elite male and female Kenyan runners. Med Sci Sports Exerc. 2003;35(2):297–304. https://doi.org/10.1249/01.MSS.0000053556.59992.A9.

5. Broxterman RM, Ade CJ, Craig JC, Wilcox SL, Schlup SJ, Barstow TJ. The relationship between critical speed and the respiratory compensation point: Coincidence or equivalence. Eur J Sport Sci. 2015;15(7):631–9. https://doi.org/10.1080/17461391.2014.966764.

6. Carter H, Pringle JSM, Jones AM, Doust JH. Oxygen uptake kinetics during treadmill running across exercise intensity domains. Eur J Appl Physiol. 2002;86(4):347–54. https://doi.org/10.1007/s00421-001-0556-2.

7. Cheng C-F, Yang Y-S, Lin H-M, Lee CL, Wang CY. Determination of critical power in trained rowers using a three-minute all-out rowing test. Eur J Appl Physiol. 2012;112(4):1251–60. https://doi.org/10.1007/s00421-011-2081-2.

8. Cumming G. The new statistics: why and how. Psychol Sci. 2013;25(1):7–29. https://doi.org/10.1177/0956797613504966.

9. Davies JI, Williams PA. Quantitative aspects of the regulation of cellular cyclic AMP levels: I. Structure and kinetics of a model system. J Theor Biol. 1975;53(1):1–30. https://doi.org/10.1016/0022-5193(75)90100-9.

10. Day JR, Rossiter HB, Coats EM, Skasick A, Whipp BJ. The maximally attainable VO_2 during exercise in humans: the peak vs. maximum issue. J Appl Physiol. 2003;95(5):1901–7. https://doi.org/10.1152/japplphysiol.00024.2003.

11. Esteve-Lanao J, Juan AFSAN, Earnest CP, Foster C, Lucia A. How do endurance runners actually train? Relationship with competition performance. Med Sci Sport Exerc. 2005;37(3):496–504.

12. Florence S, Weir JP. Relationship of critical velocity to marathon running performance. Eur J Appl Physiol. 1997;75(3):274–8. https://doi.org/10.1007/s004210050160.

13. Follador L, Alves RC, Ferreirados SS, Buzzachera CF, Andrade VFDS, Garcia EDSA, Osiecki R, Barbosa SC, de Oliveira LM, da Silva SG. Physiological, perceptual, and affective responses to six high-intensity interval training protocols. Percept Mot Skills. 2018;125(2):329–50. https://doi.org/10.1177/0031512518754584.

14. Follador L, de Borba EF, Neto ALB, da Silva SG. A submaximal treadmill test to predict critical speed. J Sports Sci. 2021;39(14):835–44. https://doi.org/10.1080/02640414.2020.1847504.

15. Follador L, Borba EF, da Silva SG. Relationship of critical speed derived from a 10-minute submaximal treadmill test to 5-km and 10-km running performances. Appl Physiol Nutr Metab. 2021;47(2):159–64. https://doi.org/10.1139/apnm-2021-0374.

16. Gaesser GA, Poole DC. The slow component of oxygen uptake kinetics in humans. Exerc Sport Sci Rev. 1996;24(1):35–71.

17. Galbraith A, Hopker J, Lelliott S, Diddams L, Passfield L. A single-visit field test of critical speed. Int J Sports Physiol Perform. 2014;9(6):931–5. https://doi.org/10.1123/ijspp.2013-0507.

18. Hartman ME, Ekkekakis P, Dicks ND, Pettitt RW. Dynamics of pleasure–displeasure at the limit of exercise tolerance: conceptualizing the sense of exertional physical fatigue as an affective response. J Exp Biol. 2019;222(Pt 3):jeb186585. https://doi.org/10.1242/jeb.186585.

19. Heck H, Mader A, Hess G, Mücke S, Müller R, Hollmann W. Justification of the 4-mmol/l lactate threshold. Int J Sports Med. 1985;6(3):117–30. https://doi.org/10.1055/s-2008-1025824.

20. Hill DW. The critical power concept. Sports Med. 1993;16(4):237–54. https://doi.org/10.2165/00007256-199316040-00003.

21. Housh TJ, Johnson GO, McDowell SL, Housh DJ, Pepper M. Physiological responses at the fatigue threshold. Int J Sports Med. 1991;12(3):305–8.

22. Hughson RL, Orok CJ, Staudt LE. A high velocity treadmill running test to assess endurance running potential. Int J Sports Med. 1984;5(1):23–5.

23. Jamnick NA, Pettitt RW, Granata C, Pyne DB, Bishop DJ. An examination and critique of current methods to determine exercise intensity. Sports Med. 2020;50(10):1729–56. https://doi.org/10.1007/s40279-020-01322-8.

24. Jolly S. A critical view of critical velocity testing to predict performance. J Sports Sci. 2013;31(7):688–9. https://doi.org/10.1080/02640414.2012.679676.

25. Jones AM, Burnley M, Black MI, Poole DC, Vanhatalo A. The maximal metabolic steady state: redefining the 'gold standard'. Physiol Rep. 2019;7(10):e14098. https://doi.org/10.14814/phy2.14098.

26. Jones AM, Doust JH. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. J Sports Sci. 1996;14(4):321–7. https://doi.org/10.1080/02640419608727717.

27. Jones AM, Vanhatalo A. The 'critical power' concept: applications to sports performance with a focus on intermittent high-intensity exercise. Sports Med. 2017;47(Suppl 1):65–78. https://doi.org/10.1007/s40279-017-0688-0.

28. Jones AM, Vanhatalo A, Burnley M, Morton RH, Poole DC. Critical power: implications for determination of VO_{2max} and exercise tolerance. Med Sci Sport Exerc. 2010;42(10):1876–90.

29. Kranenburg KJ, Smith DJ. Comparison of critical speed determined from track running and treadmill tests in elite runners. Med Sci Sport Exerc. 1996;28(5):614–8

30. Lin LI-K. A concordance correlation coefficient to evaluate reproducibility. Biometrics. 1989;45(1):255–68. https://doi.org/10.2307/2532051.

31. McLellan TOMM, Cheung KSY. A comparative evaluation of the individual anaerobic threshold and the critical power. Med Sci Sport Exerc. 1992;24(5):543–50.

32. Moritani T, Nagata A, deVries HA, Muro M. Critical power as a measure of physical work capacity and anaerobic threshold. Ergonomics. 1981;24(5):339–50. https://doi.org/10.1080/00140138108924856.

33. Laboratório Olimpico. Orientações para monitoramento da carga interna, recuperação e bem-estar. 2011. https://www.cob.org.br/pt/documentos/download/33d2e22fa4d4b.

34. Pettitt RW. Applying the critical speed concept to racing strategy and interval training prescription. Int J Sports Physiol Perform. 2016;11(7):842–7. https://doi.org/10.1123/ijspp.2016-0001.

35. Pettitt RW, Jamnick N, Clark IE. 3-min all-out exercise test for running. Int J Sports Med. 2012;33(6):426–31.

36. Poole DC, Ward SA, Gardner GW, Whipp BJ. Metabolic and respiratory profile of the upper limit for prolonged exercise in man. Ergonomics. 1988;31(9):1265–79. https://doi.org/10.1080/00140138808966766.

37. Pringle JS, Jones AM. Maximal lactate steady state, critical power and EMG during cycling. Eur J Appl Physiol. 2002;88(3):214–26. https://doi.org/10.1007/s00421-002-0703-4.

38. Smith CG, Jones AM. The relationship between critical velocity, maximal lactate steady-state velocity and lactate turnpoint velocity in runners. Eur J Appl Physiol. 2001;85(1–2):19–26. https://doi.org/10.1007/s004210100384.

39. Swain DP, Franklin BA. Comparison of cardioprotective benefits of vigorous versus moderate intensity aerobic exercise. Am J Cardiol. 2006;97(1):141–7. https://doi.org/10.1016/j.amjcard.2005.07.130.

40. Vanhatalo A, Black MI, DiMenna FJ, Blackwell JR, Schmidt JF, Thompson C, Wylie LJ, Mohr M, Bangsbo J, Krustrup P, Jones AM. The mechanistic bases of the power–time relationship: muscle metabolic responses and relationships to muscle fibre type. J Physiol. 2016;594(15):4407–23. https://doi.org/10.1113/JP271879.

41. Vickers AJ, Vertosick EA. An empirical study of race times in recreational endurance runners. BMC Sports Sci Med Rehabil. 2016;8(1):26. https://doi.org/10.1186/s13102-016-0052-y.

42. Whipp BJ. The slow component of O_2 uptake kinetics during heavy exercise. Med Sci Sport Exerc. 1994;26(11):1319–26.

43. Winter EM, Abt GA, Nevill AM. Metrics of meaningfulness as opposed to sleights of significance. J Sports Sci. 2014;32(10):901–2. https://doi.org/10.1080/02640414.2014.895118.