Physiological responses at critical running speed during continuous and intermittent exhaustion tests

Réactions physiologiques à la course à vitesse critique pendant des tests d’épuisement en continu et par intermittence

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Critical speed; Running; Intermittent; Blood lactate

Summary
Objectives. — The main aim of this study was to compare the time to exhaustion and physiological responses at critical speed during continuous and intermittent running in order to provide support to use critical speed during interval training sessions.

Equipments and Method. — Nine male runners and triathletes completed an incremental treadmill test, two track performances of 800 m and 2400 m, in order to determine the critical speed, and finally two randomized tests until exhaustion, one continuous and other intermittent running (consisting of 4 min running and 1 min of passive recovery) performed at critical speed.

Results. — The mean critical speed was $14.8 \pm 2.0 \text{ km.h}^{-1}$. The continuous and intermittent times to exhaustion were $19.3 \pm 6.4 \text{ min}$ and $37.9 \pm 14.6 \text{ min}$ respectively. The blood lactate response during continuous running showed an increase in values of about $9.0 \pm 0.8 \text{ mmol.l}^{-1}$ at the end of the exercise. On the other hand, only one of the 9 subjects analyzed, showed an abrupt increase in blood lactate during the intermittent running. The heart rate, perceived exertion and blood lactate measured at the end of both exhaustion tests were not significantly different compared with the incremental treadmill test values.

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Conclusions. — Our findings support the use of critical speed when looking for a blood lactate steady state during endurance interval sessions using a 4:1 ratio.
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Résumé
Objectifs. — Le but de cette étude est de comparer le temps jusqu’à l’épuisement ainsi que les réactions physiologiques à vitesse critique pendant un effort physique en continu et intermittents afin de justifier l’utilisation de la vitesse critique lors des sessions d’entraînement intermittent.
Équipement et méthodes. — Neuf coureurs et triathlètes masculins ont complété une épreuve de course à pied incrémentale sur tapis roulant et deux courses sur piste de 800 m et 2400 m afin d’établir la vitesse critique. Ills terminent par deux essais aléatoires effectués à vitesse critique jusqu’à l’épuisement : l’un en continu et l’autre par intermittence (course de 4 minutes, puis une minute de récupération passive).
Résultats. — La vitesse moyenne critique obtenue est de 14,8 ± 2,0 km.h⁻¹. Les temps d’épuisement pour les efforts en continu et par intermittence obtenus sont respectivement de 19,3 ± 6,4 min et 37,9 ± 14,6 min. Le taux de lactate dans le sang à la fin de la course en continu a augmenté d’environ 9,0 ± 0,8 mmol.l⁻¹. Par contre, un des 9 sujets a présenté une augmentation brutale du taux de lactate dans le sang pendant la course par intermittence. Les valeurs extrêmes de la fréquence cardiaque, de l’effort perçu et du taux de lactate dans le sang pour les deux tests d’épuisement ne sont pas significativement différentes des valeurs obtenues lors des tests sur tapis roulant.
Conclusions. — Nos résultats appuient l’utilisation de la vitesse critique afin d’établir un état d’équilibre de lactate dans le sang pendant les séances d’intervalles endurance en utilisant un ratio de 4:1.
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1. Introduction

Critical speed (CS), velocity or power (CP) have been investigated over the last four decades and questioned through different approaches in different sports and populations [1]. Many of these studies were conducted to investigate the similarity between these indices with the maximal lactate steady state intensity during swimming [2], cycling [3] and running [4]. Although the pioneering studies [5,6] had suggested that the CS or CP would be an intensity that could be maintained for a very long time, different subsequent studies have shown that during continuous exercise at this intensity, a systematic increase in blood lactate concentration occurs and times to exhaustion range between 20–40 min [7–11]. From this point of view, CP or CS can be characterised by the physiological responses to constant power exercise performed above (i.e., non-steady state) and below (i.e., steady state) CP level. They represent the boundary between heavy (below) and severe (above) intensity exercise domain [12]. Because of its practicality, the critical speed test has become widely accepted as an important performance-based field test that provides an index of endurance-specific performance [13]. Although there are different mathematical models and approaches to calculate CS [9], for practical applications, the ‘‘traditional’’ distance-time model is a more suitable for coaches and athletes [14].

Continuous running at CS or slightly above is known as ‘‘tempo training’’ and is often used by endurance runners [15]. On the other hand, runners, cyclists and triathletes have also used long interval training, close to 85–90% of maximal aerobic power or around CS intensity [15–17].

When designing long interval-training sessions, time to exhaustion (TTE) at the CS could be an interesting variable, which can be used to determine a rational basis to establish the volume for interval-training sessions in athletes. Interestingly, Dekkerle et al. [10] showed that during an intermittent swimming session consisting of 10 × 400 m (~5 min each repetition) at CS, with 50-s pauses, the blood lactate remained stable and the exercise could be maintained for about 50 min. This study demonstrated the possible application of CS for long interval session designs. In addition, de Lucas et al. [16] examined the relationship between CS and speed at maximal lactate steady state, the latter determined by continuous and intermittent models. These authors used 5 min repetitions with 1 min of passive rest, in order to identify the intermittent maximal lactate steady state in running. The results showed no significant difference between CS and the speed at intermittent maximal lactate steady state, and obtained better agreement (i.e. 95% limits of agreement) when comparing CS to continuous maximal lactate steady state. However, no acute physiological response was analysed during CS performed at continuous and/or intermittent running sessions.

The magnitude of rest periods influences the physiological responses during an interval training session [18] and a few studies have attempted to investigate the exercise:rest ratio in particular (i.e. CS). Based on previous studies [19–21] we determined that the exercise interval of 4 min would be the optimal duration for eliciting a high physiological demand (i.e. VO₂, HR). Furthermore, Seiler et al. [21] showed that a fourfold increase in passive recovery time (i.e. 1 to 4 min) had very little impact on the running velocity or physiological responses during an interval training session.
Critical speed during continuous and intermittent exhaustion running

(i.e. 6 × 4 min) performed at a self-selected running intensity. The average intensity ranged from 83 to 85% of the velocity at VO₂ max, which is very close to the CS intensity range.

To the best of our knowledge, no study investigated the acute physiological response at CS during an intermittent session in a running exercise. Based on the evidences of Dekker et al. [10] and de Lucas et al. [16], we hypothesized that during intermittent running at CS (exercise:rest ratio = 4:1) blood lactate concentration could remain steady and consequently increase TTE when compared to continuous exercise. Hence, the aim of this study was to determine and compare the TTE and physiological responses at CS during continuous and intermittent running.

2. Methods

2.1. Experimental protocol

All subjects performed an incremental treadmill test, two running performances (800 m and 2400 m) on an outdoor track and finally two TTE tests at critical speed on different days. All the TTE tests were performed randomly to avoid systematic effects (residual fatigue) on the results. Selected physiological (i.e. HR, [La]) and perceptual (i.e. RPE) responses were measured during both TTE tests. All tests were in the following ranges: same time each day over a three-week period to ensure similar environmental conditions (i.e. absence of wind). The temperature, humidity and the barometric pressure during outdoor tests ranged: 22–25 °C, 74–83% and 763–766 mmHg, respectively. Furthermore, one day before testing begun, subjects were advised to maintain a regular diet and avoid heavy training.

2.2. Subjects

Nine endurance trained subjects (3 triathletes and 6 runners) volunteered for this study. All the participants had at least three years experience with training and competitions, and trained an average of 50 ± 7 km·wk⁻¹ of running. They were highly familiar with track running, therefore an individual pacing strategy was adopted during the performances (i.e. 800 m and 2400 m). Prior to the test protocols, the subjects provided written informed consent and experimental procedures and potential risks were explained fully. The study was approved by the local ethics committee and conformed to the Declaration of Helsinki.

2.3. Incremental test

The subjects performed an incremental running test on a motor driven treadmill. The treadmill grade was kept at 1% during the test. The test started at 10 km·h⁻¹ and every 3 min the speed was increased by 1 km·h⁻¹, until the subject stopped due to volitional exhaustion. If the last stage was not fully completed, the peak treadmill speed was calculated using the formula from Kuipers et al. [22]. After each stage, samples (25 μL) of earlobe capillary blood were taken (within 15 to 20 s) and immediately analyzed for blood lactate concentration ([La]) using an enzyme electrode system (YSI, 1500 Sports, Yellow Springs, OH, USA). During the test, each subject breathed through a facemask and cardiopulmonary data was measured continuously using an open circuit system with breath-by-breath analyzer (Cosmed Quark CPET, Rome, Italy). The breath-by-breath responses were analyzed for oxygen consumption (VO₂), carbon dioxide production (VCO₂) and pulmonary ventilation (VE). The gas-analysis system was calibrated before each test using the manufacturer’s recommendations. For the incremental test, the breath-by-breath gas samples were averaged every 15 s and the HR was monitored and recorded at 5-s intervals during the exercise (Cosmed Quark CPET, Rome, Italy).

The attainment of VO₂ peak was defined using the criteria proposed by Howley et al. [23] (i.e. plateau criteria of 150 mL·min⁻¹). The vVO₂ max was defined as the minimal running speed at which VO₂ max occurred. Heart rate (HR) was recorded through the gas analyser acquisition system. HRmax was the highest 5-s average HR value achieved during test.

2.4. Critical speed determination

Athletes performed randomized time-trials running over two distances, 800 m and 2400 m, on a 200 m synthetic athletics track, in separate days. The subjects were instructed to perform their best during trials. Each subject was tested at the same time of the day (± 2 h) to minimize the effects of biological variation [24]. CS of each subject was determined by the slope of the linear distance-time relationship [2,14].

2.5. Intermittent and continuous tests to exhaustion at CS

The TTE tests were randomly performed on separate days with at least 48 hours of interval time. Following a 10-min warm-up using self-selected jogging and 5-min of passive rest, each subject ran on the same synthetic track at CS pace. Cones were set at 40-m intervals along the 200-m track (inside the first lane). The running pace was dictated by audio signals and the participants had to be within 2 m of the cones at each signal. The subjects were controlled by two researchers to ensure that the subjects ran at the required speed and encouraged them when they began to have difficulties with the pace. The tests were stopped when the subjects were unable to maintain the required pace, that is, they were unable to reach the required cones at each beep (a 2-m delay was used as an objective criteria). TTE was measured to the nearest second.

On the intermittent TTE, each subject ran at CS pace for 4 min and rested passively for 1 min. Thus, the intermittent test at CS was categorized as an exercise: rest ratio of 4:1. Immediately after each 4-min interval and at the end of test, samples (25 μL) of earlobe capillary blood was taken and then analyzed for [La] using the same equipment previously described. The same procedure as the one used during the intermittent TTE was used to control the running pace of the continuous TTE. Additionally, earlobe blood samples were collected at the twelve minute and then at the exhaustion time. All of the blood sampling was taken within 15 to 20 s. The delta of blood lactate concentration (Δ[La]) was determined by the difference between the [La]
obtained at the twelfth minute and at end exercise. The criterion for a blood lactate steady state was an increase of no more than 1 mmol.l⁻¹ in Δ[La] [25]. The rating of perceived exertion (RPE) of athletes during both tests was acquired at 4-min intervals, using the 0–10 Borg scale [26]. One assistant stayed inside the track accompanying the subject in order to ask the RPE at the established period of time. The HR was monitored and registered throughout the tests (RS-800, Polar Electro, Kempele, Finland).

2.6. Statistical analysis

All values are presented as means ± standard deviations (s). Confidence interval of 95% (95% CI) was also calculated to TTE and total distance covered during both protocols, in order to show a practical variability of these indices. Before using parametric statistical test procedures, the assumptions of normality and sphericity were verified. To compare the mean values between the continuous and intermittent running, a Student t-test for paired samples was used. A one-way ANOVA with repeated measures (Bonferroni post hoc test) was used to compare the maximal physiological variables from the incremental exercise test and the final physiological variables from the TTE tests. Pearson product moment correlation was also used to evaluate the relationship between variables at CS during both TTE tests. Analyses were carried out using the GraphPad Prism software package for Windows (v 5.0 GraphPad Prism Software Inc., San Diego, CA). Statistical significance was set at P < 0.05 for all analyses.

3. Results

The VO₂peak, HRmax and [La]peak obtained during incremental test were respectively 59.4 ± 8.2 ml·kg⁻¹·min⁻¹, 187 ± 11 beats·min⁻¹ and 9.4 ± 2.5 mmol·l⁻¹. The mean time of 800 m and 2400 m were 2.4 ± 0.1 min and 9.0 ± 1.1 min respectively. The mean CS of the sample analyzed was 14.8 ± 2.0 km·h⁻¹ and represented 88 ± 4% of speed at VO₂peak. The average time to exhaustion (37.9 ± 14.6 min and 19.3 ± 6.4 min) and total distance (8.9 ± 2.8 km and 4.7 ± 1.7 km) covered during intermittent test were larger (t = 4.2; P = 0.001 and t = 4.9; P < 0.001) than compared to the continuous protocol, respectively. The upper and lower bound of 95% CI calculated for the total distance of the continuous and intermittent tests were respectively 3.4–6.0 km and 6.8–11.1 km, while they were 14.3–24.2 min and 26.7–49.1 min for both TTE. On average the subjects completed 9 repetitions of 4-min during intermittent TTE, with the 95% CI limits ranging between 7 to 12 bouts.

Table 1 depicts the individual and mean values of the physiological responses and total time during TTE. The delta of blood lactate concentration showed an important increase from minute twelve to the end of the exercise during continuous TTE, for all subjects. Two subjects stopped the continuous exhaustion test just before the twelfth minute, limiting the statistical comparisons of Δ[La] to 7 subjects. On the other hand, five subjects out of 9 presented Δ[La] below 1 mmol·l⁻¹ during the intermittent time to exhaustion test. Furthermore, only one of the 9 subjects presented an abrupt increase in the [La] during the trial. The values obtained in the twelfth minute of TTE showed that the HR was on average 7% higher during the continuous compared to the intermittent condition (t = 3.1; P = 0.01), averaging 180 ± 11 bpm and 168 ± 10 bpm, respectively. The end HR and [La] values were not significantly different between the incremental test and the two exhaustion tests (continuous: 183 ± 9 bpm and 9.0 ± 0.8 mmol·l⁻¹; intermittent: 181 ± 13 and 8.3 ± 2.6 mmol·l⁻¹). The end value of RPE for both TTE was 9.9 ± 0.3. However, the RPE at the completion of continuous TTE compared to the iso-time of intermittent one was 6.0 ± 1.1.

A significant correlation was found between the time to exhaustion recorded for the intermittent condition, with both absolute (km·h⁻¹) and relative CS (% vVO₂peak; r = −0.76 and r = −0.81; P < 0.01, respectively). This was not obtained for the continuous condition (r = −0.09; P = 0.81) and relative speed (r = −0.16; P = 0.67) with the continuous TTE. Moreover, the correlation between both TTE trials was not significant (r = 0.42; P = 0.25). No other significant correlation was found between TTE and physiological or perceptual variables.

4. Discussion

The purpose of the present study was to compare the exercise tolerance and physiological responses at critical speed, performed during continuous and intermittent track running. According to Vanhatalo et al. [27] the ‘critical power’ concept has been suggested to have the most relevance to continuous activities lasting approximately 2 min to 30 min, although Dekkerle et al. [10] showed the possibility to use the CS during an interval swimming session. The results of the present study also suggest that CS could be applied to interval training better than continuous training, if a physiological steady state is seek for. Therefore, it is important to understand how CS can be applied in the design (number and duration of repetitions, and recovery) of interval training sessions, aimed at improving aerobic capacity. Thus, we found that TTE was twice as high during intermittent running (using ratio of 4:1) compared to continuous running. Likewise, the mean total distance covered during intermittent test was almost 9 km, compared to a total of 4.7 km achieved during continuous test. Furthermore, one could observe that the 95% CI did not overlap for both total time and distance, reinforcing the difference between these kinds of running sessions.

The 4 min interval-exercise was chosen in the present study, since it has been suggested, to be the optimal duration for training the aerobic energy system in long-lasting interval sessions [19,20]. Specifically, we sought to characterize the blood lactate response during these exercises, until exhaustion. Based on the theoretical interpretation, CS was proposed as an intensity where an individual could exercise for a very long without fatigue [5], hence the suggestion for CS to provide indirectly estimation of maximal lactate steady state [2]. However, several studies have shown that CS overestimates the intensity associated with a balance between production and removal of blood lactate, especially during continuous exercise, inducing a TTE of about 30 min [3,4,10,11,27–29]. The present study confirmed that during continuous CS running, the maximal lactate steady
state was overestimated, although the intermittent running at the ratio of 4:1 could provide lactate blood steady state for most of the subjects.

To our knowledge there is only one study investigating a similar research question. Dekkerle et al. [10], showed in swimming that intermittent CS would induce similar blood lactate responses to those expected at maximal lactate steady state. The authors utilized a swimming set of 10 × 400 m, with 50 s of passive recovery, and showed a steady state of blood lactate by approximately 50 min, although the RPE rose until the end of the set. The above study highlighted the possibility of using the CS as an index to control IT sessions performed with steady state or ‘near steady state’ of blood lactate. Additionally, de Lucas et al. [16] analyzed the relationships between critical running speed with speed at maximal lactate steady state, the latter determined through continuous and intermittent protocols. No significant relationship was found between CS and the speed at continuous maximal lactate steady state. On the other hand, a strong relationship was found between CS and intermittent maximal lactate steady state identified by a 5:1 ratio during laboratory-based measurements. The coefficient of correlation ($r = 0.84$) and the Bland-Altman analysis (bias = 0.1 km.h$^{-1}$ ± 95% limits of agreement = 1.0 km.h$^{-1}$) showed good agreement between CS and the speed at intermittent maximal lactate steady state. However, no acute physiological response and exercise tolerance during running at CS was measured in the mentioned study.

The present results agree partially with aforementioned studies. The intermittent running trial conducted at CS provided an average of 9 repetitions of 4 min in field conditions. However, 4 out of the 9 subjects did not show complete steady state on [La] over the time, i.e., the [La] increased more than 1 mmol.L$^{-1}$ between minute 12 and at the end of exercise. Despite that, it is important to note that only one subject presented an increase higher than 2 mmol.L$^{-1}$ (Table 1). The remaining three subjects presented an increase between 1.1 to 2 mmol.L$^{-1}$, showing close values to the criterion of 1 mmol.L$^{-1}$, applied to determine the maximal lactate steady state [25]. Considering the expected prediction error associated to the relationship between these indices, as reported by de Lucas et al. [16], one could assume that these subjects were running at a very close pace to [La] steady state or within the potential error range (i.e. ~1 km.h$^{-1}$).

The result of the present study found that TTE at CS during continuous running (19.2 ± 6.4 min) was very close to a study that utilized a running exercise [30], and slightly lower than studies conducted in swimming and cycling (mean value ranging 22–30 min). To our knowledge, this is the first study that analyzes both TTE and physiological responses during an intermittent running model at CS determined by field performance tests. It is worthy to note that CS was determined by two performances (i.e. ~2 min and 9 min) in the present study, so the results should be carefully interpreted.

Variation between subject’s motivation and environmental conditions in this measure provide obvious limitations. Even so, our results showed an increase of ~100% on exercise time when it was including pauses of 1 min in every 4 min of running. As expected, the peak HR and the RPE reported by subjects at the end of TTE was similar to the continuous and intermittent trials, suggesting that the perceived exertion could partially explain the exhaustion point [31]. Recently, Millet et al. [32] proposed a novel model to explain the pace strategy during ultra-marathon races, named “flush model”. In this model, the author assumes that RPE is represented by a buoy inside a water container, which increases or decreases depending on the water fill and flush rate. Running pace (i.e. speed), together with environmental conditions are factors that contribute to regulate this buoy. In a present study, if we consider that these variables were maintained constant during the TTE trials, one could suppose that the filling rate was also constant, leading the buoy to increase until the security reserve is reached (i.e. maximal perception). Thus, our results showed that RPE was lead to maximal values in both running trials, but at different times. Observ-

### Table 1 Individual and mean ± s values of time to exhaustion, final heart rate and delta blood lactate during continuous and intermittent running at critical speed.

| Subjects | Continuous | | Intermittent 4:1 |
|----------|------------|-------|-----------------|-------|
|          | TTE (min)  | HR$_{end}$ (bpm) | Δ[La] (mM) | TTE (min) | HR$_{end}$ (bpm) | Δ[La] (mM) |
| 1        | 19.7       | 184   | 1.4            | 60.0   | 183   | 0              |
| 2        | 20.7       | 184   | 3.9            | 42.5   | 185   | 0.4            |
| 3        | 11.6       | 176   | ND             | 26.2   | 179   | 1.6            |
| 4        | 26.3       | 169   | 2.8            | 53.6   | 154   | 2.0            |
| 5        | 14.3       | 175   | 1.8            | 26.6   | 169   | 1.4            |
| 6        | 30.1       | 194   | 1              | 33.5   | 199   | 0.9            |
| 7        | 22.6       | 186   | 1.5            | 28.6   | 187   | 4.3            |
| 8        | 11.2       | 197   | ND             | 18.2   | 189   | 0.8            |
| 9        | 17.0       | 185   | 3.5            | 52.0   | 186   | −0.5           |
| Mean     | 19.2       | 183   | 2.3            | 37.9$^*$| 181   | 1.2            |
| s        | 6.4        | 9     | 1.2            | 14.6   | 13    | 1.4            |

TTE: time to exhaustion; HR: heart rate; Δ[La]: difference between end lactate value and at minute twelve of TTE; ND: Missing values was due the subject had exhausted before twelve minutes.

$^*$P = 0.001 compared to continuous TTE.
ing the RPE at iso-times supports this statement. Regarding the ‘flush model’, we assumed that during the intermittent running, the 1-min recovery period decreased the filling rate, delaying the exhaustion at CS pace.

From a physiological perspective, it has been well documented, that during intermittent exercise, the lower glycolysine utilization may be explained by a relative increase in the contribution of lipids to oxidative metabolism [33,34]. This kind of exercise could also increase levels of adenosine triphosphate, creatine phosphate and citrate at the end of each rest period, which would suppress glycolysis in the early phases of the subsequent work periods [35] and probably increase the endurance time. When considering the HR response during the exercise, we observed that for a similar relative exercise time (i.e. 12 min), the intermittent running induced a smaller cardiovascular strain than the continuous condition (168 ± 10 bpm versus 180 ± 11 bpm, respectively).

Although, there are different mathematical models and approaches to calculate CS [9,36] for practical applications, the “traditional” distance-time model is a more suitable for coaches and athletes [14]. Hence, we believe that the present study contributes to practical interpretation of the distance-time model, regarding the intensity control of continuous and interval endurance training.

Relating to the percentage where CS occurs at maximal aerobic speed (vVO₂peak), most studies reported values between 84—91% [1]. The present study found that CS averaged at 88% of vVO₂peak. Additionally, we found a significant and negative correlation between CS (absolute and relative to VO₂peak) and intermittent TTE. Therefore, exercising closer to maximal aerobic speed, leads to lesser TTE [37]. Furthermore, this relationship was found only with intermittent TTE. In relation to continuous TTE we did not find any correlation with physiological variables. Pringle et al. [37] found a significant correlation between VO₂peak values and TTE at CP during continuous cycling exercise, suggesting that the fitter subjects could sustain exercise at CP for longer than the less aerobically trained individuals. We have failed to find similar relationships in the present study. Thus, the reason for these different results and correlations are not clear, and need to be more carefully studied.

5. Conclusion

The results of the present study show that CS is more likely associated with lactate steady state during intermittent running, than continuous running. Thus, an interval training protocol (e.g., repetitions of 4 min; 100% of CS, with 1 min of passive recovery) could be used as an alternative tool to provide a ‘near balance’ on blood lactate for most athletes. Furthermore, twice the time to exhaustion may be expected during an interval session compared to continuous running at the CS intensity, although the physiological and perceptual measurements at exhaustion were similar between trials. Thus, the RPE should be considered, to monitor the intensity relative to maximal sustained time. This information can be useful for coaches and physical trainers when designing IT sessions applied to endurance athletes.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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