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Research article

Is the critical running speed related to the intermittent maximal lactate steady state?

Ricardo D. de Lucas ✉, Naiandra Dittrich, Rubens B. Junior, Kristopher M. de Souza and Luiz Guilherme A. Guglielmo
Sports Center, Federal University of Santa Catarina, Physical effort Laboratory, Florianópolis, Brazil

Abstract
The purpose of the present study was to compare the critical speed (CS) with the speed at the maximal lactate steady state (vMLSS) determined by a continuous and an intermittent model in trained runners. Eight male endurance runners (30.3 ± 10.6 years; 65.0 ± 8.5 kg; 1.73 ± 0.6 m; 11.3 ± 4.0% body fat) volunteered for this investigation and performed an incremental treadmill test, as well as 2-5 30-min constant speed tests to determine the MLSS continuous and MLSS intermittent (5 min of running, interspaced by 1 min of passive rest). The CS was determined by 2 maximal running efforts of 1500 and 3000 m performed on a 400 m running track. The CS was calculated as the slope of the linear regression of distance versus time. Statistical analysis revealed no significant difference between CS and MLSS determined by intermittent running (15.2 ± 1.0 $km \cdot h^{-1}$ *vs.* 15.3 ± 0.7 $km \cdot h^{-1}$, respectively), however, both were significantly higher than continuous MLSS (14.4 ± 0.6 $km \cdot h^{-1}$). There was also a significant correlation between CS and MLSS intermittent ($r = 0.84$, $p = 0.008$). On the basis of the present results, we conclude that for practical reasons (low cost, non-invasive) the CS is an interesting and alternative method to prescribe endurance interval training at maximal lactate steady state intensity, in preference to a continuous protocol.

Key words: Maximal lactate steady state, critical speed, interval training.

Introduction

The maximal lactate steady state velocity or speed (vMLSS) can be defined as the highest running velocity at which blood lactate concentration ([La]) remains stable during the last 20 min of constant load exercise (Beneke, 1995; Weltman, 1995). Indeed, the vMLSS has been considered the boundary between heavy and severe intensity domains (Pringle and Jones, 2002) and also the upper limit of stability in metabolic responses and pulmonary gas exchange. Besides, it is frequently used for the prescription of aerobic training, especially for endurance athletes (Beneke, 1995; Beneke et al., 2001; Billat et al., 2004; Jones and Doust, 1998; Philp et al., 2008).

It is important to highlight that vMLSS is usually determined by continuous, long duration protocols. Nevertheless, the prescription of aerobic training in many sports is also conducted intermittently, thus it is necessary to make adjustments in training intensity. Interval training (IT) has been frequently used by endurance athletes (swimmers, cyclists, rowers, runners, and triathletes) as a strategy to increase training intensity (Billat, 2001; Billat et al., 2004; Philp et al., 2008; Seiler and Hetlelid, 2005). Intermittent exercise is the basis of IT and involves repeated bouts of high intensity (equal to or greater than vMLSS) interspersed with periods of recovery (passive or active), which allow proportionally greater durations than do activities at the same absolute load or similar durations with higher loads (Beneke et al., 2003; Billat et al., 2003).

Thus, considering the importance of intermittent training to endurance sports it is necessary that the vMLSS also be determined using this model in order to increase the specificity of IT. According to this, Beneke et al. (2003) found that the work load at MLSS determined in an intermittent protocol ($vMLSS_{int}$) was approximately 9% higher than that determined during a continuous protocol ($vMLSS_{con}$). This study highlighted the importance of knowledge of the physiological responses during intermittent exercise for the evaluation and prescription of aerobic training at vMLSS.

Moreover the vMLSS, the critical velocity or speed (CS) has also been used to evaluate aerobic fitness and also to prescribe endurance training intensity (Poole et al., 1990; Denadai et al., 2003). A running CS was first described by Hughson et al. (1984) as an adaptation of the critical power concept developed by Monod and Scherer (1965). In this model, initially proposed for the cycle ergometer, the asymptote of the nonlinear relationship between power vs. time to exhaustion, was named ‘critical power’. Later, this concept was applied in a different way to other sports such as swimming (Wakayoshi et al., 1993), track running (Kranenburg and Smith, 1996) and track cycling (de Lucas et al., 2002) assuming a linear relationship between distance and time. Although Wakaoyshi et al. (1993) applied the critical power concept in field tests and suggested that the CS corresponded to the anaerobic threshold intensity to this sport, numerous studies have shown that this index overestimates the actual $vMLSS_{con}$ in swimming (Dekerle et al., 2005; 2010), cycling (de Lucas et al., 2002; Brickley et al., 2002; Dekerle et al., 2003) and running (Smith and Jones, 2001; Denadai et al., 2005). On the other hand, Dekerle et al. (2010) showed stability of [La] over 50 min duration in IT sets (10 x 400 m with 50 s pauses), suggesting that CS may represent an intensity similar to $vMLSS_{int}$. However, up to this date, no study has attempted to compare the CS with a direct method of determination of vMLSS in an intermittent model. Thus, we hypothesized a significant relationship between CS and the $vMLSS_{int}$ in a group of trained runners.

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Hence, the main aim of the present study was to compare the CS with the speed at MLSS determined during a continuous versus intermittent model in trained runners.

Methods

Subjects

Eight male endurance trained runners, with at least 3 years of national experience volunteered in the present study (30.3 ± 10.6 years; 65.0 ± 8.5 kg; 1.73 ± 0.06 m; 11.3 ± 4.0% body fat). Preceding the period of the study, the athletes had a weekly training volume of 40 km. All of the tested athletes were familiarized with the experimental procedures.

Besides, prior to any testing all participants was familiarized with the experimental procedures and gave written informed consent as well as being informed of the associated risks and benefits of participation. The research project was approved by the Ethics Committee for Scientific Research at the Federal University of Santa Catarina (protocol 222/2008).

Experimental design

In order to avoid undue fatigue before testing, subjects were instructed to avoid heavy training during the preceding 24 hours. Athletes were advised to maintain a regular diet during the day before testing and to refrain from smoking and caffeinated drinks during the two hours preceding testing. All tests were performed over a three week period and all tests were performed at the same hour of the day (i.e. 9-11 am) in order to avoid circadian variation in performance output (Carter et al., 2002).

Firstly were performed anthropometric measures (body mass, stature, and skinfold measures to estimate percent body fat) followed by an intermittent treadmill test for the assessment of maximal oxygen uptake (VO_2max), velocity at maximal oxygen uptake (vVO_2max), maximal ventilation (VEmax), maximal heart rate (HRmax) and onset of blood lactate accumulation (OBLA). Based on the determination of OBLA, on different days, three to five submaximal tests were performed to determine the speed at maximal lactate steady state using both a continuous ($vMLSS_{con}$) and an intermittent protocol ($vMLSS_{int}$).

Following the determination of the vMLSS in both models two field performances at 1500 m and 3000 m were performed on different days.

Experimental protocol

Anthropometric measures

Body mass (kg) was measured to the nearest 0.1 kg using a calibrated balance (Soehnle, Germany) and body height was measured to the nearest 0.1 cm (Sanny, EUA). Body fat mass was assessed by the measurements of seven skinfold (chest, mid-axillary, supra-iliac, abdomen, triceps, sub-scapular and thigh) with a scientific adipometer accurate to 1mm (CESCORF, Porto Alegre, Brazil). Body density was estimated from a specific equation to male athletes proposed by Jackson and Pollock (1978), and the value was applied to estimate body fat by the Siri (1956) equation.

Measurement of VO_2max, vVO_2max, VEmax, HRmax, and OBLA

An intermittent treadmill exercise test was performed on a motorized treadmill (Imbramed Millenium Super, Brazil). The treadmill was set at a 1% gradient and an initial starting speed of 10.0 $km \cdot h^{-1}$; treadmill speed was subsequently increased by 1.0 $km \cdot h^{-1}$ every 3 minutes until subjects achieved volitional exhaustion. Between each stage there was a rest interval of 30 seconds to collect 25 µL of capillary blood from the ear lobe to measure [La]. The analysis of lactate was performed using an electrochemical analyzer (YSI 2700 STAT, Yellow Springs, OH, USA) and OBLA was determined as the speed corresponding to a 3.5 $mmol.L^{-1}$ concentration of blood lactate (Heck et al., 1985).

Respiratory gases were measured breath by breath (K4b2, Cosmed, Rome, Italy) during the incremental test using a pre-calibrated online metabolic system, and the data reduced to 15s averages. Achievement of VO_2max was considered as the attainment of at least two of the following criteria: 1) a plateau in VO_2 with increasing work-load, 2) a respiratory change ratio above 1.10, 3) a heart rate ± 10 bpm of age predicted HRmax (220-age) (Howley et al., 1995).

The vVO_2max was identified as the lowest speed where VO_2max occurred and was maintained for at least one minute. Heart rate (HR) was recorded continuously during the test by a HR monitor incorporated into the gas analyser. The HRmax was the highest 5-sec. average HR value achieved during test.

Determination of $vMLSS_{con}$ and $vMLSS_{int}$

Several constant speed tests were performed using both continuous and intermittent protocols. For the determination of $vMLSS_{con}$, each constant speed test lasted 30 min. The speed of the first test corresponded to a [La] of 3.5 $mmol \cdot L^{-1}$ (OBLA) obtained during the incremental maximal test. A fixed [La] of 3.5 $mmol \cdot L^{-1}$, instead of 4.0 $mmol \cdot L^{-1}$, has been used in incremental tests with 3-min stages (Heck et al., 1985; Smith and Jones, 2001). Blood samples were collected on the 10th and 30th min of these tests.

The initial speed for determination of $vMLSS_{int}$ was 5% above the $vMLSS_{con}$. The identification of $vMLSS_{int}$ was similar to the continuous protocol, but with a total duration of 35 min due to the 1-min rest period (passive recovery) after every 5 min of running, characterizing an work:rest ratio of 5:1. Blood samples for measurement of [La] were collected on the interval of the second, fourth and last 5 min effort .

If during the first constant speed test of both protocols a steady state or a decrease in [La] was observed, further subsequent 30-min tests with a 5% higher speed were performed on separate days until no [La] steady state could be maintained. On the other hand, if the first constant speed test resulted in a clearly identifiable increase in the [La] and/or could not be completed due to exhaustion, further tests were conducted with a reduction of 5% in the speed. The vMLSS in both protocols was determined as the highest speed that could be maintained with [La] increase lower than 1.0 $mmol \cdot L^{-1}$ during the final 20 min of the appropriate test (Beneke et al., 2003; Figueira et al., 2008; Heck et al., 1985). The [La] value of MLSS ([La]MLSS) was calculated as the average [La] measured on the 10^{th} and 30^{th} min of the $vMLSS_{con}$ and on the second and last 5 min effort during $vMLSS_{int}$.

Determination of CS

The CS was determined by the linear model of distance (d) versus time (t) proposed by Wakayoshi et al. (1993) for field tests. The subjects were instructed to run distances of 1500 m and 3000 m on a 400 m outdoor running track as fast as possible. Each performance test was conducted on the same day by all subjects to ensure similar environmental conditions (i.e. absence of wind). The temperature, humidity and the barometric pressure on each day ranged: 20-23°C, 60-70% and 763-765 mmHG, respectively.

The subjects were highly familiarized to track running, thus an individual pacing strategy was adopted, with no influence of the researchers. The distances were chosen according to the procedures outlined by Housh et al. (1990), which proposed at least five minutes difference between performance times. All performance times were recorded by three manual digital watches (Timex ®, Marathon) with a precision of ±1.0 millisecond. The HR was recorded and stored (Polar®, model RS400) every second during the two performances. Before each performance, athletes warmed up for 10 min (~ 65% of HRmax).

The CS was calculated using the program Microsoft™ Exel®, as the slope of the linear regression (d = AWC + CS.t) of distance *vs*. time relationship. AWC means anaerobic work capacity, and represents the y-intercept obtained from the linear relationship.

Statistical analysis

Data are presented as mean ± standard deviation. Normality was assessed by Shapiro Wilk test. Comparisons among variables ($vMLSS_{con}$, $vMLSS_{int}$ and CS) were performed with one-way analysis of variance (ANOVA) followed by post-hoc tests (Bonferroni). In order to compare the differences between continuous and intermittent model, Student´s t-test for paired sample was used. The magnitude of this difference was assessed by the Effects Size (ES) and the scale proposed by Cohen (1988) was used for interpretation. Pearson product moment correlation was also used to evaluate the strength of the association between CS and vMLSS. Besides, the bias ± 95% limits of agreement were used to assess the relationship between each vMLSS protocol with the CS. Analyses were carried out using the GraphPad Prism software package for Windows (v5.0 GraphPad Prism Software Inc, San Diego, CA). Statistical significance was set at $p < 0.05$ for all analyses.

Results

Mean maximal aerobic speed value (vVO_2max) reached by the subjects was 17.5 ± 0.9 $km \cdot h^{-1}$ and corresponded to a VO_2max of 63.1 ± 4.5 $mL \cdot kg^{-1} \cdot min^{-1}$. The maximal values of VO_2, VE, HR and [La] attained during the incremental test are reported in Table 1.

Table 1. Mean (±SD) values of physiological variables attained during the incremental maximal test on treadmill.

Variables	Values
$\mathbf{VO_{2max}}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	63.1 (4.5)
$\mathbf{VO_{2max}}$ ($L \cdot min^{-1}$)	4.6 (.7)
$\mathbf{VE_{max}}$ ($L \cdot min^{-1}$)	148.5 (15.9)
$\mathbf{HR_{max}}$ ($beats \cdot min^{-1}$)	182 (13)
$\mathbf{[La]_{peak}}$ ($mmol \cdot L^{-1}$)	8.6 (1.9)

VO_{2max} = maximal oxygen uptake; VE_{max} = maximal ventilation; HR_{max} = maximal heart rate; $[La]_{peak}$ = peak blood lactate concentration.

The speed, VO_2, VE and [La] obtained in $vMLSS_{con}$ were significantly lower than $vMLSS_{int}$ (Table 2). Additionally the ES showed a large difference between speeds of continuous versus intermittent running model. The mean HR was similar between the two models.

The mean CS of the subjects was 15.2 ± 1.0 $km \cdot h^{-1}$. This value showed no significant difference with $vMLSS_{int}$, however, both were significantly higher than $vMLSS_{con}$. Furthermore, there were strong correlations between $vMLSS_{con}$ and $vMLSS_{int}$ (r = 0.87, p = 0.005). Conversely, CS showed no significant correlation with $vMLSS_{con}$, however, there was a significant correlation between CS and $vMLSS_{int}$ (r = 0.84, p = 0.009).

Complementing these findings, Figure 1 depicts the Bland-Altman plot presenting the bias and limits of agreement between CS and vMLSS (continuous and intermittent). Analyzing Figure 1 it is possible to observe a bias ± 95% of limits of agreement of -0.7 ± 1.5 $km \cdot h^{-1}$ (CS and $vMLSS_{con}$) and 0.1 ± 1.0 $km \cdot h^{-1}$ (CS and $vMLSS_{int}$).

Discussion

The purpose of the present study was to compare the critical speed with the speed at MLSS determined during continuous and intermittent running. The results of this investigation showed significant associations and similarities between CS and $vMLSS_{int}$ (15.2 ± 1.0 and 15.3 ± 0.7 $km \cdot h^{-1}$, respectively) indicating the possibility of using this index to predict the $vMLSS_{int}$, whilst the $vMLSS_{con}$ (14.4 ± 0.6 $km \cdot h^{-1}$) was significantly lower than both other indices. Further, the Bland Altman plot showed

Table 2. Speed and physiological variables values in continuous and intermittent running, showed as mean (±SD) and effect sizes (ES).

Variables	Continuous	Intermittent	ES	Descriptor
Speed ($km \cdot h^{-1}$)	14.4 (.6) *	15.3 (.7)	1.38	Large
$\mathbf{VO_2}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	53.4 (4.1) *	56.6 (4.3)	.76	Moderate
VE ($L \cdot min^{-1}$)	101.6 (14.8) *	109.6 (16.6)	.51	Small/Moderate
HR ($beats.min^{-1}$)	166 (9)	169 (8)	.47	Small
[La] ($mmol \cdot L^{-1}$)	4.2 (1.0) *	5.1 (1.8)	.64	Small/Moderate

VO_2 = oxygen uptake; VE = ventilation; HR = heart rate; [La] = blood lactate concentration.
* $p < 0.05$ compared to intermittent exercise.

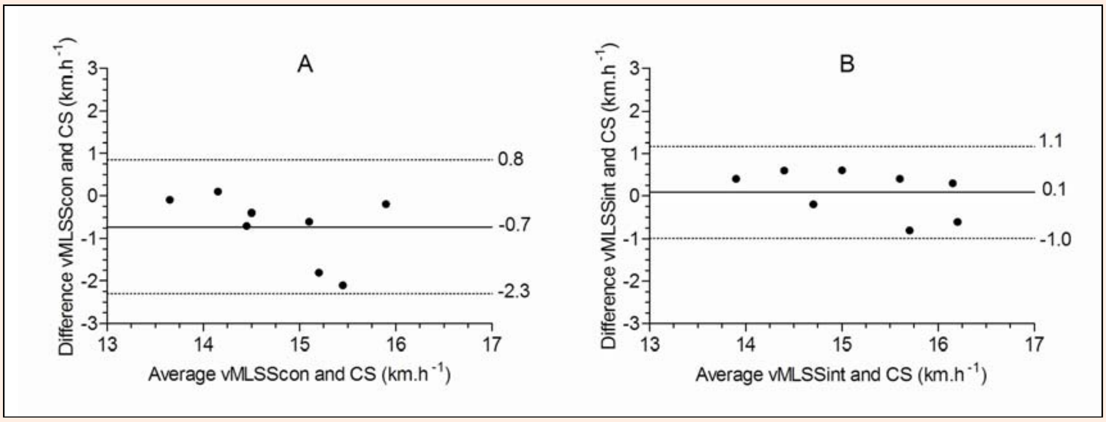

Figure 1. Analysis of Bland-Altman plot of $vMLSS_{con}$ and $vMLSS_{int}$ with CS.

good agreement between CS and $vMLSS_{int}$, thus justifying the use of CS as an important index to control IT. However, even considering the small bias between these indices, the confidence interval (95%) reveals a possible prediction error of 1 $km \cdot h^{-1}$, or approximately 6%. Nevertheless, the results show that the intermittent MLSS is similar to CS.

Previous results available in the literature demonstrate that CS is not the intensity that can be maintained for a long period of time without fatigue, as proposed by pioneering studies (Monod and Scherer, 1965; Moritani et al., 1981).Wakayoshi et al. (1993) were the first authors to compare the intensities of MLSS and swimming CS. Although the authors concluded that CS may correspond to the exercise intensity at MLSS, the protocol used during the research had short pauses between the 400 m repetitions for blood sampling. These brief rest periods seemed to increase the blood lactate removal via oxidation (Brooks, 2002), consequently leading to a higher intensities corresponding to MLSS (Beneke et al., 2003). Subsequent studies showed an overestimation of CS, when compared to OBLA or $vMLSS_{con}$ intensity during swimming (Greco et al., 2010; Dekerle et al., 2010), cycling (de Lucas et al., 2002; Brickley et al., 2002), and running (Smith and Jones, 2001; Denadai et al., 2005).

Supporting these findings, results from studies performed in swimming and cycling have shown that in exercises performed at CS the time to exhaustion ranges between 20 and 40 min. Brickley et al. (2002) found a mean time to exhaustion of 29.3 ± 8.2 min and a final [La] of 7.3 ± 1.6 $mmol \cdot L^{-1}$, whilst the end-VO_2 corresponded to 91% of the VO_2max. Observing this together with others studies (Jenkins and Quigley, 1990; de Lucas et al., 2002) it seems that the CS is situated at an intensity slightly above the continuous MLSS.

In addition, the difference between the vMLSS determined in both modes, was 6% and represented a large effect size (ES) (Cohen, 1988). Furthermore, the $vMLSS_{con}$ was situated at ~ 82,2% of maximal aerobic speed (i.e. vVO_2max) assessed during treadmill incremental test, whilst the $vMLSS_{int}$ was ~ 87,4% of vVO_2max. Some years ago, Beneke et al. (2003) demonstrated in cycling that the work rates corresponding to the MLSS determined during an intermittent protocol with passive recovery (30 or 90 s rest every five minutes of exercise) were about 8-10% higher (300 and 310 W, respectively) than that determined in a 30 min continuous protocol (277 W).

Taking this perspective, Dekerle et al. (2010) conducted an interesting study with 6 swimmers and found [La] stability over 50 min during IT sets (10 x 400 m) at the CS intensity. In contrast when the athletes swam at this intensity continuously, the [La] stability was not maintained and a time to exhaustion less than 30 min was recorded, suggesting that CS is at an intensity corresponding to the intermittent lactate steady state. Thus, confirming these results, the present study found that the running CS corresponded to the $vMLSS_{int}$ (15.2 ± 1.0 and 15.3 ± 0.7 $km \cdot h^{-1}$, respectively). Additionally, a significantly correlation was found between these indices ($r = 0.84$, $p < 0.05$) and also a good agreement between them (Figure 1).

Previous studies have found that $MLSS_{int}$ is an intensity about 3% to 4% higher than the $MLSS_{con}$ in swimming (Dekerle et al., 2010; Greco et al., 2010), 6% to 10% in cycling (Beneke et al., 2003) and, according to present findings, approximately 6% in running. It is important to emphasize that these differences are likely associated to the exercise mode and to the different work:rest ratio, as well as the durations of exercise intervals, used in previous studies.

The determination of vMLSS can be quite important for the prescription of training for endurance athletes (Philp et al., 2008). However, although the vMLSS is the "gold standard" method to determine aerobic capacity, its methodology is not suitable for routine diagnostic use because of its time-consuming nature (several days to complete the series of prolonged bouts) and because of the requirement for numerous blood samples (Dekerle et al., 2003; Dekerle et al., 2005). Thus, for practical reasons (low cost and non-invasive) CS is an interesting and alternative method to prescribe IT at maximal lactate steady state intensity. Few studies have discussed the practical application of CS to prescribe both continuous and interval training. Considering the literature, the mean value of time to exhaustion at CS is between 15 and 30 min (Brickley et al., 2002; Bull et al., 2008; de Lucas et al., 2002), and the IT session at CS intensity, could be planned based on total volume close to 30 min, i.e. 6 x 5 min or 10 x 3 min. The work:rest ratio could be about 5:1 to 2:1, depending on the approach. The present study used a model of 5:1 and so the present findings should be restricted to that general characteristic. The choice of characteristics of intermittent exercise used during the present investigation, was supported by traditional long interval sessions commonly used by endurance runners, as repetitions of 1000-1600 m (i.e. around 5 min), depending on the performance level (Billat, 2001). Dekerle et al. (2010), used a model of exercising at CS during swimming, based on distance intervals (i.e. 10 x 400 m with rest of 50 s). The models of both studies could be considered similar, since swimmers from the Dekerle et al. (2010) study, performed intervals somewhat close to 5 min and the rest period was close to 1 min. Hence, we consider the practical application of CS for sport coaches, an important issue to discuss, focusing the topic between athletes and coaches.

Conclusion

The difference observed between vMLSS (continuous and intermittent), and the strong relationship and agreement between CS and $vMLSS_{int}$ allow the use of this index (i.e. CS) to estimate the $vMLSS_{int}$. Hence, caution must be taken to prescribe interval training using a continuous MLSS determination, to avoid a possible underestimation of training load. Thus, training at CS intensity using interval sessions at least of 5:1 ensures that a maximal lactate steady state is being stressed.

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Key points

- Critical running speed (CS) is related to the intermittent maximal lactate steady state using work: rest ratio of 5:1.
- CS can be used to prescribe interval training at maximal lactate steady state speed.
- A reduction of 6% of CS can be useful to predict $MLSS_{con}$ and for prescribing continuous training sessions.

AUTHORS BIOGRAPHY

Ricardo Dantas DE LUCAS
Employment
PhD Student of the Physical Education Post-graduation program, Federal University of Santa Catarina
Degree
MSc
Research interests
Exercise physiology, endurance training
E-mail: ricardo@tridantas.com.br

Naiandra DITTRICH
Employment
Student of the Physical Education Post-graduation program, Federal University of Santa Catarina
Degree
BSc
Research interests
Exercise physiology, maximal lactate steady state
E-mail: naia_dittrich@yahoo.com.br

Rubens BABEL JUNIOR
Employment
Student of Federal University of Santa Catarina
Degree
BSc
Research interests
Exercise physiology
E-mail: rubao_babel@yahoo.com.br

Kristopher Mendes de SOUZA
Employment
Student of the Physical Education Post-graduation program, Federal University of Santa Catarina
Degree
BSc
Research interests
Exercise physiology, critical power
E-mail: kristophersouza@yahoo.com.br

Luiz Guilherme Antonacci GUGLIELMO
Employment
Professor of the Physical Education Post-graduation program, Federal University of Santa Catarina
Degree
PhD
Research interests
Exercise physiology, Maximal lactate steady state
E-mail: luizguilherme@cds.ufsc.br

⌧ **Ricardo D. de Lucas**
Sports Center, Federal University of Santa Catarina, Physical effort Laboratory, Florianópolis, Brazil