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Agreement analysis between critical power and intensity corresponding to 50% Δ in cycling exercise

Análise de concordância entre a potência crítica e a intensidade correspondente ao 50% Δ no exercício de ciclismo

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Abstract – The purpose of this study was to determine the level of agreement between critical power (CP) and intensity corresponding to 50% of the difference (50% Δ) between oxygen uptake (VO_2) at lactate threshold (LT) and maximal oxygen uptake (VO_{2max}) in untrained subjects during cycling exercise. Fifteen healthy male subjects (age: 26.0 ± 3.5 years; body weight: 76.6 ± 10.4 kg; height: 178.2 ± 7.6 cm) volunteered to participate in the study. Each subject performed a series of tests to determine LT, VO_2LT, CP, VO_2CP, 50% Δ, $VO_2$50% Δ, and VO_{2max}. The values of LT, VO_2LT, CP, VO_2CP, 50% Δ, $VO_2$50% Δ and VO_{2max} were 109 ± 15 W, 1.84 ± 0.23 L.min^{-1}, 207 ± 17 W, 2.78 ± 0.27 L.min^{-1}, 206 ± 19 W, 2.77 ± 0.29 L.min^{-1}, and 3.71 ± 0.49 L.min^{-1}, respectively. No significant difference was found between CP and 50% Δ (t = 0.16; p = 0.87) or between VO_2CP and $VO_2$50% Δ (t = 0.12; p = 0.90). However, the bias ± 95% limits of agreement for comparison between CP and 50% Δ and between VO_2CP and $VO_2$50% Δ were 1 ± 27 W (0.3 ± 14.1%) and 0.01 ± 0.24 L.min^{-1} (0.2 ± 8.9%), respectively. In summary, the mean CP and 50% Δ values were not significantly different. However, considering the limits of agreement between the two intensities, CP estimated based on 50% Δ might result in a remarkable error when the absolute variability of individual differences is taken into account.

Key words: Exercise intensity; Lactate threshold; Maximal oxygen uptake.

Resumo – A proposta deste estudo foi determinar o nível de concordância entre a potência crítica (PC) e a intensidade correspondente a 50% da diferença (50% Δ) entre o consumo de oxigênio (VO_2) no limiar de lactato (LL) e o consumo máximo de oxigênio (VO_{2max}) em sujeitos não treinados durante o exercício de ciclismo. Quinze sujeitos saudáveis do sexo masculino (idade: 26,0 ± 3,5 anos; massa corporal: 76,6 ± 10,4 kg; estatura: 178,2 ± 7,6 cm) participaram deste estudo. Cada sujeito realizou uma série de testes para determinar o LL, VO_2LL, PC, VO_2PC, 50% Δ, $VO_2$50% Δ e VO_{2max}. Os valores de LL, VO_2LL, PC, VO_2PC, 50% Δ, $VO_2$50% Δ e VO_{2max} foram 109 ± 15 W, 1,84 ± 0,23 L.min^{-1}, 207 ± 17 W, 2,78 ± 0,27 L.min^{-1}, 206 ± 19 W, 2,77 ± 0,29 L.min^{-1} e 3,71 ± 0,49 L.min^{-1}, respectivamente. Nenhuma diferença significativa foi encontrada entre a PC e o 50% Δ (t = 0.16; p = 0.87) e entre o VO_2PC e o $VO_2$50% Δ (t = 0.12; p = 0.90). Entretanto, o bias ± 95% dos limites de concordância para as comparações entre a PC e o 50% Δ e entre o VO_2PC e o $VO_2$50% Δ foram 1 ± 27 W (0,3 ± 14,1%) e 0,01 ± 0,24 L.min^{-1} (0,2 ± 8,9%), respectivamente. Em resumo, os valores médios de PC e 50% Δ não foram significativamente diferentes. No entanto, a PC estimada pelo 50% Δ pode resultar em um erro significativo quando a variabilidade individual absoluta é considerada.

Palavras-chave: Consumo máximo de oxigênio; Intensidade de exercício; Limiar de lactato.

INTRODUCTION

Exercise intensity domains are defined based on their different metabolic and physiological profiles[1,2] and are classified as moderate, heavy, and severe[1]. The nature and magnitude of the blood lactate ([La]) and oxygen uptake (VO_2) responses within these three exercise intensity domains are very specific[1-4] and, consequently, promote different adaptations to training[4]. The lactate threshold (LT) is considered the upper boundary of the moderate-intensity domain[1-4], while the critical power (CP; the asymptote of the power-time relationship) represents the boundary between the heavy- and severe-intensity domains[1-4]. Thus, the accuracy of determining these boundary work rates (i.e., LT and CP) has been considered essential for both aerobic training prescription and experimental designs.

Particularly, given that CP represents an important demarcator of metabolic and physiological stability and a fundamental index for understanding high-intensity exercise tolerance[3,5-8], its relevance cannot be overemphasized. However, the determination of CP is especially demanding in terms of the subject's effort and testing time[9]. As an alternative, studies investigating the metabolic and physiological responses to heavy- and severe-intensity exercise have established work rates using the "percentage delta" (% Δ) method[10,11]. The % Δ considers both VO_2 at LT (VO_2LT) and maximal oxygen uptake (VO_{2max})[10,11], such that the 50% Δ intensity refers to the work rate calculated to require 50% of the difference between VO_2LT and VO_{2max}.

Using this approach, it is assumed that the overall metabolic and physiological demands experienced by subjects exercising at the same % Δ are similar. However, this assumption can be questioned because it does not account for some aspects (e.g., inter-subject variability, exercise mode, and aerobic training status) that can influence the % Δ corresponding to CP[9,11,12]. As a consequence, different subjects exercising at a given % Δ might actually be in different exercise intensity domains. Nevertheless, based on the % Δ concept, some studies involving untrained subjects have assumed the work rate associated with 50% Δ to be the boundary between the heavy- and severe-intensity domains[10,12,13,15,16]. However, to our knowledge, the validity of this approach is missing since direct comparison between CP and 50% Δ in untrained subjects has never been appropriately investigated.

Thus, it is important to determine the relationship between CP and 50% Δ since assigning the boundary between the heavy- and severe-intensity domains based on a fixed % Δ can result in dramatic variations in metabolic and physiological response profiles and in the exercise tolerance of different subjects. Therefore, the purpose of this study was to determine the level of agreement between CP and 50% Δ in untrained subjects. We hypothesized that the CP and 50% Δ would be similar when the mean values of the two parameters are compared. On the other hand, when the limits of agreement described by Bland and Altman[17] are considered, the absolute variability of individual differences between CP and 50% Δ would result in a noteworthy error.

METHODOLOGICAL PROCEDURES

Subjects

Fifteen healthy male subjects (age: 26.0 ± 3.5 years; body weight: 76.6 ± 10.4 kg; height: 178.2 ± 7.6 cm) volunteered to participate in the study. The subjects participated in exercise at a recreational level and were familiar with cycle ergometry and the exercise testing procedures used in our laboratory. After they were fully informed about the risks and stresses associated with the study, the subjects gave their written informed consent to participate. The experimental protocol was approved by the Research Ethics Committee of the Federal University of Santa Catarina (process number 2188) and was conducted in accordance with the Declaration of Helsinki.

Experimental design

The subjects were required to visit the laboratory on five different occasions. First, they performed a submaximal step incremental test (four to six stages) to determine LT, followed by a maximal ramp incremental test for the measurement of VO_{2max} and maximal power output (P_{max}). During the following sessions, the subjects performed four randomized maximal constant work rate tests to exhaustion at 75%, 85%, 95% and 105% P_{max} for determination of the curvature constant of the power-time relationship (W') and CP. The pedal cadence was maintained between 70 and 75 rpm for all tests. The subjects were instructed to avoid any consumption of caffeine or alcohol and strenuous exercise in the 24 h preceding a test session and to arrive at the laboratory in a rested and fully hydrated state, at least 3 h postprandial. All tests were performed at the same time of day under controlled environmental laboratory conditions (temperature: 19-22°C; relative humidity: 50-60%) to minimize the effects of diurnal biological variation on the results[18]. With the exception of the submaximal and maximal incremental exercise tests, which were performed on the same day, the subjects performed only one test on any given day. The tests were separated by intervals of 24-48 h but completed within a period of 2 weeks.

Equipment

All tests were performed on an electromagnetically braked cycle ergometer (Excalibur Sport, Lode BV, Groningen, The Netherlands). The cycle ergometer was calibrated according to manufacturer recommendations. Respiratory and pulmonary gas exchange variables were measured continuously using a breath-by-breath analyzer (Quark PFTergo, Cosmed, Rome, Italy). Before each test, the O_2 and CO_2 analysis systems were calibrated using ambient air and a gas of known O_2 and CO_2 concentrations according to manufacturer instructions. The Quark PFTergo turbine flow meter was calibrated using a 3-L syringe (Cosmed, Rome, Italy). Breath-by-breath VO_2 data were analyzed throughout the tests (Data Management Software, Cosmed, Rome, Italy). Capillary blood samples (25 μL) were obtained from the earlobe of each subject and [La] was measured using an electrochemical

analyzer (YSL 2700 STAT, Yellow Springs, OH, USA). The analyzer was calibrated as recommended by the manufacturer.

Submaximal and maximal incremental exercise tests

First, each subject performed a submaximal step incremental test to determine LT. The test started at 60 W and was increased by 20 W every 3 min during four to six stages. Capillary blood samples were collected within the final 20 s of each stage for [La] determination. The LT was determined from the relationship between [La] and the work rate and was defined as the first sudden and sustained increase in [La] above the baseline concentrations[12]. After 30 min of rest, the subjects performed a maximal ramp incremental test for the assessment of VO_{2max} and P_{max}. The test started at 90% LT during the first 4 min and was thereafter continuously increased by a rate of 25 W.min^{-1} until the volitional exhaustion. Each subject was verbally encouraged to undertake maximal effort. Breath-by-breath VO_2 data were reduced to 15-s stationary averages and VO_{2max} was defined as the highest average 15-s VO_2 value recorded during the ramp incremental test. The attainment of VO_{2max} was assumed using the criteria proposed by Midgley et al.[19] and Poole et al.[20]. The P_{max} was defined as the highest work rate attained in the ramp incremental test. The 50% Δ was determined as the work rate corresponding to VO_2 halfway between VO_2LT and VO_{2max}. The VO_2 at 50% Δ ($VO_2$50% Δ) was determined using the VO_2-work rate relationship during the ramp incremental test.

Determination of CP and *W'*

The subjects performed four randomized maximal constant work rate tests until exhaustion at 75%, 85%, 95% and 105% P_{max}. These work rates were chosen to induce a time to exhaustion (t_{lim}) ranging from 2 to 12 min[5,8,21]. Each test started with a 5-min warm-up at LT, followed by 5 min of rest. Further, after 3 min pedaling at 20 W, the power output was adjusted to one of the previously established work rates and the subjects were instructed to continue until they were unable to maintain the required work rate. Timing began when the pedal cadence reached 70 rpm and stopped when the subject could no longer maintain a pedal cadence higher than 67 rpm despite verbal encouragement[9]. The t_{lim} was measured to the nearest second. Individual *W'* and CP estimates were derived from the four constant work rate prediction trials by least-squares fitting of the following regression models:

a) nonlinear power output (P) vs. time to exhaustion (t_{lim}):
$$t_{lim} = W' / (P - CP) \tag{1};$$
b) linear work (W) vs. time to exhaustion (t_{lim}):
$$W = (CP \times t_{lim}) + W' \tag{2};$$
c) linear power output (P) vs. 1 / time to exhaustion (t_{lim}):
$$P = (W' / t_{lim}) + CP \tag{3}.$$

The W' and CP estimates from the three equations were compared to select the best fit using the model associated with the lowest standard error of the estimate (SEE) for CP[8,22,23]. Breath-by-breath VO_2 data were recorded continuously during all tests and were reduced to 15-s stationary averages. The peak VO_2 was defined as the highest average 15-s VO_2 value recorded during the tests. The VO_2 at CP (VO_2CP) was determined using the VO_2-work rate relationship during the ramp incremental test.

Statistical analysis

All data are expressed as the mean ± standard deviation. The Shapiro-Wilk test was applied to ensure a Gaussian distribution of the data. A paired Student t-test was used to compare CP and 50% Δ. The bias and limits of agreement between the two variables were calculated as described by Bland and Altman[17]. The Pearson product moment correlation coefficients were used to assess the significance of relationships between the variables. All analyses were carried out using the GraphPad Prism software package for Windows (v.5.0, GraphPad Prism Software, Inc., San Diego, CA, USA). The level of significance was set at $p < 0.05$.

RESULTS

The values of P_{max}, VO_{2max}, LT and VO_2LT determined during the incremental tests are shown in Table 1. The values of peak VO_2 and t_{lim} recorded during the constant work rate tests performed at 75%, 85%, 95% and 105% P_{max} are shown in Table 2. As expected, peak VO_2 in these constant work rate tests was not significantly different from the VO_{2max} measured during the ramp incremental test (F = 1.74; p = 0.21).

Table 1. Physiological parameters determined during the incremental tests

Parameter	
P_{max} (W)	322 ± 26
VO_{2max} (L.min^{-1})	3.71 ± 0.49
LT (W)	109 ± 15
LT (% P_{max})	34.1 ± 4.5
VO_2LT (L.min^{-1})	1.84 ± 0.23
VO_2LT (% VO_{2max})	50.1 ± 6.8

P_{max} = maximal power output; VO_{2max} = maximal oxygen uptake; LT = lactate threshold; VO_2 = oxygen uptake.

Table 2. Oxyg en uptake and time to exhaustion in the constant work rate tests

% P_{max}	VO_2 (L.min^{-1})	t_{lim} (min)
75% P_{max}	3.71 ± 0.45	10.5 ± 1.8
85% P_{max}	3.69 ± 0.39	5.6 ± 1.2
95% P_{max}	3.67 ± 0.50	3.8 ± 0.7
105% P_{max}	3.54 ± 0.42	2.6 ± 0.5

P_{max} = maximal power output; VO_2 = oxygen uptake; t_{lim} = time to exhaustion.

Table 3 shows the values of W', CP, VO_2CP, 50% Δ, and $VO_2$50% Δ. The goodness-of-fit of the power-time relationship was $r^2 = 0.99 \pm 0.01$. The SEE and 95% confidence interval associated with the estimated parameters of the power-time relationship were 1.9 ± 1.2 kJ and 1.6 to 2.0 kJ, respectively, for W' and 4 ± 3 W and 3 to 4 W for CP. In addition, CP was equivalent to $50.1 \pm 7.9\%$ Δ. Thus, no significant difference was found between CP and 50% Δ (t = 0.16; p = 0.87). Similarly, there was no significant difference between VO_2CP and $VO_2$50% Δ (t = 0.12; p = 0.90).

Table 3. Parameters derived from the power-time relationship and intensity corresponding to 50% Δ

Parameter	
W' (kJ)	21.3 ± 4.2
CP (W)	207 ± 17
CP (% P_{max})	64.3 ± 2.7
VO_2CP (L.min^{-1})	2.78 ± 0.27
VO_2CP (% VO_{2max})	75.2 ± 3.9
50% Δ (W)	206 ± 19
50% Δ (% P_{max})	64.1 ± 3.5
$VO_2$50% Δ (L.min^{-1})	2.77 ± 0.29
$VO_2$50% Δ (% VO_{2max})	75.1 ± 3.4

W' = curvature constant of the power-time relationship; CP = critical power; P_{max} = maximal power output; VO_{2max} = maximal oxygen uptake; VO_2 = oxygen uptake; 50% Δ = work rate corresponding to VO_2 halfway between VO_2 at LT and VO_{2max}.

Figure 1 illustrates the bias ± 95% limits of agreement for comparison between CP and 50% Δ (1 ± 27 W; 0.3 ± 14.1%) and between VO_2CP and $VO_2$50% Δ (0.01 ± 0.24 L.min^{-1}; 0.2 ± 8.9%), respectively. The CP was significantly correlated with 50% Δ (Figure 2A; r = 0.70; p < 0.01). Likewise, VO_2CP and $VO_2$50% Δ were highly correlated (Figure 2B; r = 0.91; p < 0.01).
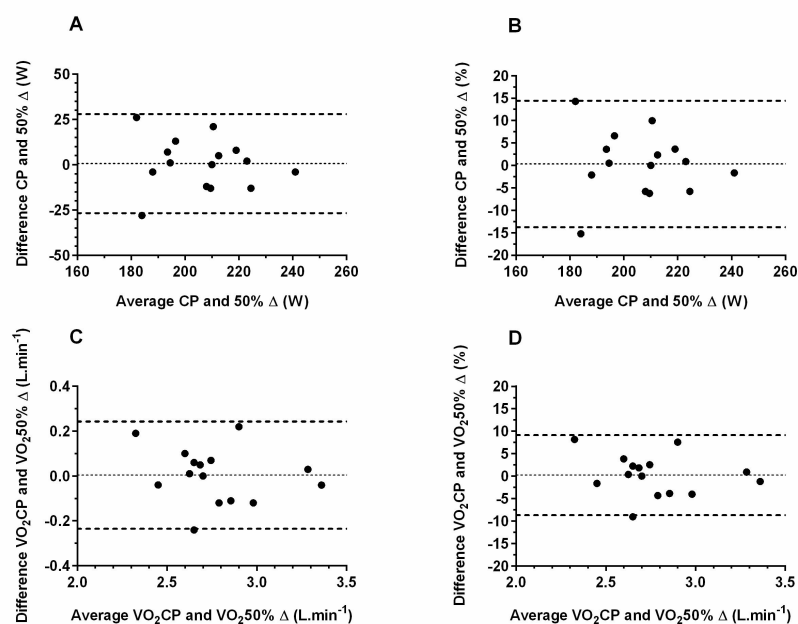

Figure 1. Bland-Altman plots of CP versus 50% Δ (A and B) and VO₂CP versus VO₂50% Δ (C and D). The central dotted line in all panels represents the mean difference between parameters and the dashed lines indicate the 95% limits of agreement.
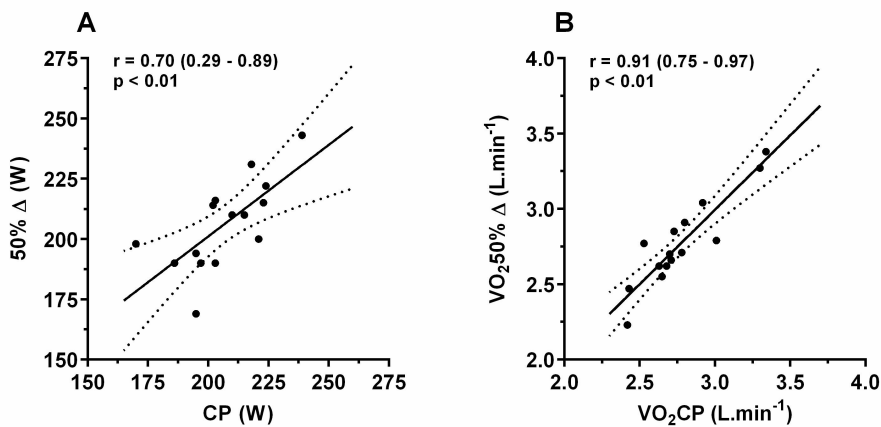
Figure 2. Relationship between CP and 50% Δ (A) and VO₂CP and VO₂50% Δ (B). The solid line in the two panels represents the trend line of the relationship between parameters and the dotted lines indicate the 95% confidence interval.

DISCUSSION

The purpose of this study was to investigate the relationship between CP and 50% Δ in untrained subjects. To our knowledge, this was the first study to assess the limits of agreement between the two exercise intensities. The paired Student t-test revealed no significant difference between CP and 50% Δ either for work rate or VO₂, suggesting that 50% Δ can be used to determine the boundary between the heavy- and severe-intensity domains. However, the limits of agreement of Bland-Altman analysis showed that estimating CP by the calculation of 50% Δ for a single subject could result in an error of up to ± 27 W or 14% (Figure 1). Obviously, the potential for error is particularly high and such estimates would be unwise if precision were needed in training prescription and experimental designs.

Individual agreement analysis indicated that CP was situated below the 50% Δ (ranging from 12 to 28 W or from 6 to 16%) in four subjects and was above it in an additional six subjects (ranging from 5 to 26 W or from 2 to 13%). In the remaining subjects (n = 5), the 50% Δ was found within an acceptable range of CP error calculation (less than or equal to the SEE for CP). This result clearly highlights significant interindividual variability when CP is estimated based on 50% Δ. Therefore, assigning exercise intensity based on a fixed % Δ might result in differences in the metabolic and physiological stress experienced by different subjects.

Some physiological mechanisms associated with the aerobic nature of LT, CP and VO₂max may help explain the interindividual variability in % Δ corresponding to CP. These mechanisms are likely to include muscle fiber type composition, gas exchange and blood flow characteristics, as well as muscle contractile and metabolic properties[1,2]. The dynamics of these physiological mechanisms influence the range of difference between VO₂LT and VO₂max[1,2]. In this respect, subjects with greater aerobic capacity (i.e., LT, CP and VO₂max) are believed to have a higher proportion of type I fibers, enhanced blood flow to and from the exercising muscles, higher mitochondrial density and oxidative enzyme activity, faster VO₂ kinetics, and a higher muscle buffer capacity[1,2]. Therefore, the rate of accumulation of

fatigue-related metabolites can be both slower and lower during exercise[1,2].

Interestingly, many of the landmark investigations of supra-LT VO_2 kinetics used work rates determined by % Δ, mainly the work rate corresponding to 50% Δ[1,2,12,14]. However, the results of the present study indicate that two subjects exercising at 50% Δ might actually be in different exercise intensity domains. Consequently, the two subjects would demonstrate different metabolic and physiological response profiles and tolerable duration of exercise. This is a matter of concern since experimental interventions such as 'priming' exercise and training, which depend on the exercise intensity domain investigated[28,29], have been used in an attempt to determine the main limiting factors of supra-LT VO_2 kinetics and exercise tolerance. Thus, especially in studies investigating topics such as VO_2 kinetics and exercise tolerance, incorrect inferences and interpretations could be made when the exercise intensity is normalized by % Δ.

It is also known that CP typically occurs between approximately 40-60% Δ, with a mean of 50% Δ[6,11]. This is confirmed by the present data since only two subjects of the 15 subjects studied had a CP outside this range (CP was equivalent to 32% and 64% Δ in the two subjects). Thus, according to Lansley et al.[11], the prescription of exercise at ≤ 40% Δ and ≥ 60% Δ should result in metabolic and physiological response profiles that are consistent with heavy- and severe-intensity exercise, respectively, in the majority of healthy subjects. However, considering some studies with small sample sizes (many studies have used seven subjects)[12,21], any subject with a CP outside this range could compromise the results. Therefore, we propose the use of a "safety zone" of ± 20% Δ from the 50% Δ in studies that normalize the exercise intensity by the % Δ method (i.e., 30% Δ if heavy-intensity exercises are required and 70% Δ for those intended to be severe intensity). Although inaccurate, this is a safer approach to ensure similar metabolic and physiological responses within the heavy- and severe-intensity exercise domains.

A limitation of the present study was the lack of rigorous control for nutrition, hydration and resting states of the subjects, especially during the constant work rate tests. However, the use of four predictive trials to model the power-time relationship resulted in SEE values of 1.9% and 8.9% for CP and W', respectively. This is consistent with the proposed SEE values of less than 2% and 10% for CP and W', respectively[30]. Additionally, the findings and suggestions of the present study are restricted to cycling exercise and untrained subjects, since CP occurs at a higher relative intensity in trained subjects[3,9]. Indeed, de Lucas et al.[3] and Caputo and Denadai[9] have demonstrated that in well-trained cyclists CP averaged at 65% and 75% Δ, respectively. These results suggest that the aerobic training status modifies the relationship between CP and the difference between VO_2LT and VO_{2max}. Moreover, the higher upper boundary of the heavy-intensity domain (expressed as % Δ) observed in these studies suggests that the improvement in LT can be greater than the improvement in CP during longer term training programs performed by cyclists[3,9]. However, further

studies are needed to verify the relationship between CP and the difference between VO_2LT and VO_{2max}, especially in other exercise modalities and populations.

CONCLUSION

In summary, CP was not significantly different from 50% Δ (work rate and VO_2) when the mean values were analyzed using an inferential statistical approach. However, considering the limits of agreement between the two exercise intensities, CP estimated based on 50% Δ might result in a remarkable error when the absolute variability of individual differences is taken into account. We therefore do not recommend the interchangeable use of CP and 50% Δ when exercise intensity accuracy is needed.

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