Determination of the power-duration relationship in upper-limb exercises

Determination da relação potência-duração em exercício com membros superiores

Domingos Belasco Junior¹, Fernando R. Oliveira², José A. N. Serafini³, Antonio C. Silva⁴

Abstract

Objectives: To determine the power-duration relationship in upper limb exercises and to investigate the relationships between parameters derived from this function with physiological indicators of aerobic fitness. Methods: Ten healthy men (26.2±2.3 years, 75.0±11.8 kg, 178.2±11.5 cm and 15.0±5.7% body fat) performed a ramped test on an arm cycle ergometer with increments of 20 W/min. Subsequently, five tests with constant load were performed until exhaustion, with 70, 80, 90, 95 and 100% difference between VT1 and VO₂peak. The critical power (CP) was obtained by means of linearization of the power-duration function. Results: The power-duration relationship was described using an adjusted function (r=0.98±0.02). The VO₂ at CP (2.66±0.62 l/min) was higher than VT1 and VO₂peak. The CP workload (103.0±26 W) was significantly different from VT1 (69.5±21 W) and VO₂peak workloads (151.0±26.3 W), but was no different of VT2 (103.5±30.8 W). The association between critical power and aerobic condition indexes were always significant when expressed as VO₂ (0.73 to 0.78, p<0.05) and in W (0.83 to 0.91, p<0.05). Determination of CP in upper-limb dynamic exercises is simple and inexpensive, and can be used by physical therapists for prescribing and evaluating upper-limb training programs. Conclusions: The power-duration relationship in upper-limb exercises can be described by a hyperbolic function and it is associated with physiological indicators of aerobic fitness.

Key words: critical power; upper limbs; metabolic thresholds.

Resumo

Objetivos: Determinar a relação potência-duração em exercícios de membros superiores (MMSS) e verificar a relação dos parâmetros derivados dessa função com indicadores fisiológicos de aptidão aeróbia. Métodos: Dez homens saudáveis (26,2±2,3 anos, 75,0±11,8 kg, 178,2±11,5 cm e 15,0±5,7% de gordura) realizaram um teste de rampa em cicloergômetro de braço com incrementos de 20 W/min. Posteriormente, cinco testes de carga constante até a exaustão a 70, 80, 90, 95 e 100% da diferença entre LV1 e o VO₂pico foram realizados. A potência crítica (PC) foi obtida por meio da linearização da função potência-duração. Resultados: A relação potência-duração foi descrita pela função ajustada (r=0,98±0,02). O VO₂ na PC (2,66±0,62 l/min) foi maior do que no LV1 (1,62±0,38 l/min) e LV2 (2,36±0,59 l/min, respectivamente), mas menor do que o VO₂pico (3,06±0,62 l/min). A carga da PC (103,0±26,0 W) foi diferente da encontrada em LV1 (69,5±21 W) e VO₂pico (151,0±26,3 W), mas não da em LV2 (103,5±30,8 W). A associação entre a PC e esses indicadores de aptidão aeróbia foram todas significantes quando expressas em VO₂ (0,73 a 0,78; p<0,05) e em W (0,83 a 0,91; p<0,05). A determinação da PC em exercícios dinâmicos de MMSS é simples e de baixo custo, podendo ser utilizada pelo fisioterapeuta na prescrição e avaliação do treinamento de MMSS. Conclusão: A relação potência-duração em exercícios com os MMSS pode ser descrita por uma função hiperbólica e está associada a indicadores fisiológicos da aptidão aeróbica.

Palavras-chave: potência crítica; membros superiores; limiares metabólicos.

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Introduction

When assessing and prescribing exercises for prevention of orthopedic, cardiothoracic or neurological lower-limb (LL) dysfunctions and functional rehabilitation among such individuals, it is necessary for physical therapists to know about the physiological basis that characterizes load threshold determinations between upper-limb (UL) work intensity domains. The most commonly used parameters are the physiological transition threshold (PTT) and the maximum oxygen uptake or peak (VO\textsubscript{max}/peak)\textsuperscript{1}. Another parameter used is the power that in theory could be sustained over the long term without fatigue. This is known as the critical power (CP) or critical velocity (CV). It is determined by analyzing the rectangular hyperbolic relationship between power developed (W) and time elapsed until exhaustion (t) for high-intensity and constant load exercises\textsuperscript{2-4}. In other words, it appears that when analyzing the resulting equation, the endurance (capability to perform an exercise for a prolonged period of time) relies directly on the curvature constant and inversely on the power applied above CP\textsuperscript{2-3}. Within this context, CP is found to be above the ventilatory anaerobic threshold (VT1), in which the load is approximately 60-65\% of the difference between VT1 and VO\textsubscript{max}, at least for LL exercises performed by young individuals\textsuperscript{4-6}. Thus, Whipp and Ozyener\textsuperscript{7} proposed that VT1 would mark the transition between moderate and high-intensity exercises, and that the CP would divide intense and very intense domains close to the respiratory compensation point (VT2)\textsuperscript{6}. This would extend to the VO\textsubscript{max} load. The W-t relationship has been extensively studied in exercises performed using small or large muscle groups at different levels of physical activity, in response to several interventions, even in patients with ventilatory restriction\textsuperscript{5,9}. Moreover, as seen in relation to PTT, it has been demonstrated that CP is sensitive to the effects of training. In this respect, there is little data in the literature regarding whether the response to high intensity UL exercises would be hyperbolic\textsuperscript{10-14}. In addition, little is known about the relationship between the parameters describing the W-t relationship for UL and other aerobic fitness indicators\textsuperscript{8}. There are significant differences in maximum and submaximal physiological responses to LL exercises, in comparison with exercises that use a smaller amount of muscle mass (notably UL exercises), have already been described\textsuperscript{15-18}. Furthermore, LL ergometers are a useful tool for assessing and training individuals with functional limitation of LL movements, or for lung disease and cardiac patients, thereby assisting in the process of cardiopulmonary rehabilitation\textsuperscript{19}. In this light, the objectives of the present study were to analyze the power-duration relationship in constant load exercises performed in UL ergometer and to investigate the relationship between parameters that derive from this function and from physiological indicators of aerobic fitness. In addition, this study investigated whether CP for UL can be used as an assessment tool for the endurance and whether, in this type of activity, CP is associated with PTT and VO\textsubscript{peak}.

Methods

The sample consisted of 10 young male adults (22 to 32 years of age) with no orthopedic restrictions on performing UL exercises. They were classified as physically active, with scores ranging from 8 to 12 according to the Baecke, Burema and Frijters\textsuperscript{20} physical activity questionnaire. The study was conducted at the Stress Physiology Study Center (CEFE) after its approval by the Ethics Committee of the Federal University of São Paulo (UNIFESP) (040/00). The subjects were included only after they had signed an informed consent statement. A single physician performed a clinical examination on all subjects, composed of full anamnesis and general physical examination.

Anthropometric data on the subjects were obtained using calibrated scales (Filizola, Brazil), and the body mass index was calculated (Table 1). The subjects were then subjected to an incremental ramped test up to the limit of tolerance. The incremental ramping rate (20 W/min) was adjusted between the subjects so that the test duration would be between 4 and 10 minutes.

The metabolic, ventilatory and cardiovascular responses during the UL cycle ergometer test (MET 300, Cybex, Lumex, Ronkonkoma, NY, USA) were obtained via an integrated digital system for cardiopulmonary exercise tests (Vista CX, Vacumed, Hans Rudolph, USA). Metabolic and cardiopulmonary variables were obtained and sampled as arithmetic averages of values determined every 20 seconds. The gas analyzers were calibrated before each test by using a precise mixture of gases (16% O\textsubscript{2} and 4% CO\textsubscript{2}). The flow meter was also calibrated before each test using a syringe with a pre-established volume of three liters (Wyandotte model 7200, Hans Rudolph, USA), with different flow settings (slow, moderate and fast). The following variables were determined:

| Table 1. Mean and standard deviation (SD) values of age, fitness level according to the Baecke, Burema and Frijters\textsuperscript{20} score and body mass index (BMI). |
| --- | --- | --- |
| Age (years) | Baecke score | BMI (kg/m\textsuperscript{2}) |
| Mean | 26.7 | 9.2 | 22.5 |
| ±SD | 2.8 | 1.2 | 1.4 |
O₂ uptake (VO₂; l/min STPD); carbon dioxide production (VCO₂; l/min STPD); respiratory quotient (R); minute ventilation (VE; l/min BTPS); respiratory equivalent for O₂ and CO₂ (VE/VO₂ and VE/VCO₂); partial pressure of O₂ and CO₂ (PO₂ and PCO₂; mmHg) and heart rate (HR; bpm). The VO₂ of the final last 20 seconds of the ramp was considered to be the VO₂ peak. The VT1 VO₂ was estimated by means of the pulmonary gas exchange method, using readings of the VCO₂ inflection point in relation to VO₂ (modified V-slope) and using the ventilator method. In this, both VE/VO₂ and PO₂ increased, while VE/VCO₂ and PCO₂ remained stable. To determine VT1, two regions were excluded from the analysis: the initial two minutes of the protocol, when slower VCO₂ kinetics affect the relationships of pulmonary gas exchange, and the points beyond the respiratory compensation point (RCP). The readings were performed independently by two experienced observers who did not know the identity of the subject under evaluation, or the other results relating to this subject. Taking into account that, for rapid-increment protocols, the load corresponding to the VO₂ point values is the one that was developed during the preceding time constant, the VT1 load was considered to be the one manifested 45 seconds prior to the VO₂ that was associated with VT1. VT2 was identified by determining the point at which a progressive increase in the equivalent VE/VCO₂ occurred, with a drop in PCO₂ and/or a second abrupt increase in VE after VT1, plotted as a function of VCO₂.

Subsequently, each subject underwent a set of five different constant load tests performed up to the limit of tolerance: each test was taken on a different day in a randomized sequence. The protocol was composed of five rectangular loading functions, with a minimum interval of three days between loads. The aim was to provide better graphic distribution and greater validity for the CP and anaerobic threshold (PC, in W) were determined from the slope and the intercept, respectively, of the line obtained from the difference between least squares.

### Table 2. Mean (±SD) values of VO₂ and power (W) at peak effort, CP, VO₂ peak, VT1 and VT2.

<table>
<thead>
<tr>
<th>Peak effort</th>
<th>CP</th>
<th>VT1</th>
<th>VT2</th>
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<tr>
<td>VO₂ (l/min)</td>
<td>3.06±0.62</td>
<td>2.66±0.62</td>
<td>1.62±0.38</td>
</tr>
<tr>
<td>Power (W)</td>
<td>151.00±26.30</td>
<td>103.00±26.00</td>
<td>69.50±21.00</td>
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</table>

VO₂ CP, through identifying the time at which VO₂ stabilized. This was found to be between 5 and 10 minutes for all subjects.

Finally, all the subjects underwent an additional test at a load that was 5% greater than the load equivalent to the intercept of the W-1/t relationship. Neither the subjects nor the investigator were informed of the duration of the test or the power that they should develop. The subjects received encouragement from the investigator, to ensure that they would perform the test to the best of their abilities.

The tests were performed with the subjects maintaining a cycling frequency of 80 rpm, in accordance with a preestablished protocol for UL ergometry. All the tests were preceded by three minutes under baseline resting conditions and two minutes of load-free exercise, during which the ventilatory and metabolic parameters were verified. The time taken to reach fatigue was determined as the interval between the imposition of the load and the point at which the subject could not maintain the required pace of cycling (drop greater than 10%).

The W-t relationship was linearized by means of a load (in watts) versus the reciprocal of time (1/t), i.e.:

\[ W = W' + PC \]

Therefore, the curvature constant (W’, in kJ) and its asymptote (PC, in W) were determined from the slope and the intercept, respectively, of the line obtained from the difference between least squares.

### Statistical analysis

After verifying that the variables presented normal distribution (Kolmogorov-Smirnov test), the means and the standard deviations were identified. The mean values were compared using one-way ANOVA for paired samples. The levels of association between CP, VT1, VT2 and VO₂ peak were determined using the Pearson correlation test. For all tests, significance level of 5% (α=0.05) was established.

### Results

The relationship between the power applied and its respective time duration (W-t) was described by a rectangular hyperbolic function for all assessed subjects, with the following values: CP=103±26 W; W’=7.08±2.14 kJ; and r=0.98±0.02. Table 2 shows the values found for the study variables from the progressive test and in relation to CP.
The value of VO₂ at CP (VO₂CP) was significantly greater than the values found for VT1 (P<0.001) and VT2 (p<0.05) and lower than to VO₂ peak (p<0.05). No significant difference in W was found between CP and VT2. There were significant associations between the VO₂ and W values at CP and between the values of these variables at peak effort, VT1 and VT2 (Table 3).

The volunteers continued to perform the rectangular loading test corresponding to CP for 42.9±12.9 minutes. One subject (10%) could not complete 30 minutes of exercise at CP, reaching fatigue after 20 minutes of exercise. The other subjects tolerated at least 30 minutes in the rectangular test. However, at the load that was 5% greater than CP, the subjects reached fatigue after 13.7±1.4 min (range: 11.7 to 16.0 min).

Discussion

There has been a series of discussions regarding the mathematical model that would best represent the relationship between W and t. The number of loads that would be ideal for composing the distribution of points on the W versus t graph and the amount of time for which a CP load would be bearable. The high r values for all subjects demonstrated that by using the reciprocal of time, the relationship was properly linearized with a hyperbolic function. The findings from the present study emphasize that, similar to LL exercises, the relationship between W and the inverse of time duration (1/t), in accordance with previous observations made by other authors in LL-related research.

VO₂max is an aerobic index that, when measured during UL exercises, presents values that are around two thirds of the values obtained during LL exercises among healthy individuals. The smaller muscle mass of the UL can cause localized fatigue and cause exercises to be interrupted before the maximum cardiac output is reached. This is why the parameter is named VO₂peak, regardless of whether a plateau is reached.

Loads that led to CP were calculated as fractions of the difference between maximum power and VT1. VO₂PC and VO₂peak were associated (r=0.73; p<0.05), with significant differences between the parameters, of 2.66±0.617 l/min and 3.06±0.619 l/min, respectively. VO₂CP was also significantly greater and correlated with VO₂VT1 (1.621±0.378 l/min; r=0.76) and VO₂VT2 (2.36±0.587 l/min; r=0.78). The same trend was observed among the loads of these variables, with greater association values found between them (Table 2). These results suggest that the nature of CP is predominantly aerobic, as previously reported. Reinforcing this model, W’ did not correlate significantly to any of the aerobic parameters used (r=0.04-0.25). This result suggests that these indexes provide different metabolic representations.

VT2 was calculated from the behavior of ventilatory variables during the ramp protocol. At submaximal intensities, this usually reveals VO₂ values that are lower than those obtained in rectangular loading functions of longer duration, i.e. over five minutes, like the VO₂CP measurement that was used in this study. The phenomenon that explains this discrepancy between protocols is the small component of the VO₂ kinetics that occurs above VT1. This makes VO₂ dependent not only on load but also on the duration of the exercise, which can determine different levels of stress when assessing these variables.

The associations found between CP and VT1 and VT2 are in agreement with data for UL found by Moritani et al. Among well-trained young students, Dekerele et al. found that CP was greater than VT1 and similar to VT2, with non-significant associations between CP and VT1 (r=-0.08) and LV2 (r=0.07). In contrast to these results, Dekerele et al. demonstrated that the intensity at CP was similar to the VT1 intensity, while Nakamura et al. found that CP was significantly greater than VT1 (r between 0.86 and 0.93) and smaller than VT2 (r between 0.79 and 0.85). These conflicts relating to the physiological domain of CP can be extended to comparisons with the intensity of maximum lactate steady state (MLSS). Although a high level of association was found between these variables (r=0.95), it has been demonstrated that CP is greater in intensity or that no significant differences occur between these variables. Moreover, it was not possible to find a steady state of blood lactate concentration [lact] in rectangular loadings at CP, despite the similarity with the intensity of MLSS at VO₂ and perceived exertion.

Factors related to costs and the small numbers of laboratories that perform ergospirometry tests using UL ergometers hinder and sometimes even prevent physical therapists from prescribing appropriate exercises during cardiopulmonary rehabilitation programs. Methodologically, CP determination and its use as an estimate of the MLSS is advantageous for physical therapists who prescribe UL exercises during cardiopulmonary rehabilitation programs. It is easy and feasible to apply CP determinations, and to produce valid information for monitoring aerobic endurance ability and the individual

Table 3. Level of correlation between VO₂ and W corresponding to peak effort, VT1 and VT2 in upper-limb cycle ergometry.

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<th>Peak effort</th>
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<tbody>
<tr>
<td>VO₂CP (l/min)</td>
<td>0.73</td>
<td>0.76</td>
<td>0.78</td>
</tr>
<tr>
<td>WCP (W)</td>
<td>0.91</td>
<td>0.83</td>
<td>0.86</td>
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response to training, while avoiding, for instance, problems of estimation based strictly on blood lactate values\textsuperscript{23}. However, it should be noted that the results from the present study did not make it possible to establish whether CP corresponds to a greater metabolic need associated with steady lactate. Even though it was verified that VO\textsubscript{2} stabilized under constant loading at CP, no direct measurements of lactate were made, either at this or at other, lower or higher loads. Nonetheless, the mean time duration at CP was 42.9 ± 12.9 min (minimum of 20 min). None of the subjects maintained the load of 5% above CP for more than 20 minutes (13.7 ± 1.4 min), which favors the use of CP as an approximation for the intensity of the MLSS in UL exercises. Regardless of the way in which CP is expressed, it appears to belong to a transition zone between intense and very intense domains.

Regarding the CP load, the value found for the pulmonary exchange rate was 0.98 ± 0.02, which corresponded to an intensity predominantly from the use of energy from carbohydrate metabolism\textsuperscript{34}. Over a period of time sustaining this load, this energy path is progressively depleted, and its depletion may be the main cause of fatigue. From the time taken to reach exhaustion and the features of the UL exercises practiced at intensities higher than CP, the main reason for terminating the exercises was correlated with increases in metabolic acidosis.

Future investigations with larger samples and involving the W-t relationship for UL exercises should be performed using different protocols, cycling paces and interruption criteria. They should also include the use of analogue scales of perceived effort and located electromyography\textsuperscript{30,11,12,34,35}, particularly emphasizing additional studies on the relationship between the maximum lactate steady accumulation rate and CP.

The power applied and the respective duration of a tolerance relationship for high-intensity dynamic UL exercises were characterized by a rectangular hyperbolic function. The y asymptote of this relationship (CP) represented a load similar to VT2, which was likely to be sustained for a prolonged period of time and with r similar to the one commonly found in LL. CP was significantly associated with indicators of aerobic metabolism, such as VO\textsubscript{2peak}, VT1 and VT2.

References


