Critical Power Concept Adapted for the Specific Table Tennis Test: Comparisons Between Exhaustion Criteria, Mathematical Modeling, and Correlation with Gas Exchange Parameters

Authors

A. Zagatto[1], M. F. Miranda[2], C. A. Gobatto[3]

Affiliations

[1] Federal University of Mato Grosso do Sul, Department of Physical Education, Campo Grande, Brazil
[2] Dom Bosco Catholic University, Physical Education, Campo Grande, Brazil
[3] UNICAMP – State University of Campinas, Department of Sport Sciences, Campinas-SP, Brazil

Key words
- critical frequency
- specific test
- peak oxygen uptake

Abstract

The purposes of this study were to determine and to compare the critical power concept adapted for the specific table tennis test (critical frequency – *Cf*) estimated from 5 mathematical models and using 2 different exhaustion criteria (voluntary and technical exhaustions). Also, it was an aim to assess the relationship between *Cf* estimated from mathematical models and respiratory compensation point (RCP), peak oxygen uptake ($\dot{V}O_{2PEAK}$) and minimal intensity at which $\dot{V}O_{2PEAK}$ ($f\dot{V}O_{2PEAK}$) appears. 9 male table tennis players [18(1) years; 62.3(4.4) kg] performed the maximal incremental test and 3–4 exhaustive exercise bouts to estimate *Cf*s (balls·min^{-1}). The exhaustion time and *Cf* obtained were independent of the exhaustion criteria. The *Cf* from 3-parameter model [45.2(7.0)-voluntary, 43.2(5.6)-technical] was lower than *Cf* estimated by linear 2-parameter models, frequency-time^{-1} [53.5(3.6)-voluntary, 53.5(3.5)-technical] and total ball thrown-time [52.2(3.5)-voluntary, 52.2(3.5)-technical] but significantly correlated. *Cf* values from 2 linear models were significantly correlated with RCP [47.4(3.4) balls·min^{-1}], and *Cf* values of the linear and nonlinear models were correlated with $f\dot{V}O_{2PEAK}$ [56.7(3.4) balls·min^{-1}]. However, there were no significant correlations between *Cf* values and $\dot{V}O_{2PEAK}$ [49.8(1.1) ml·kg^{-1}·min^{-1}]. The results were not modified by exhaustion criteria. The 2 linear and non-linear 2-parameter models can be used to estimate aerobic endurance in specific table tennis tests.

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Correspondence
Prof. Alessandro Zagatto, PhD
Federal University of Mato Grosso do Sul
Department of Physical Education
Av Costa e Silva s/n
79079-900 Campo Grande
Brazil
Tel.: +55/67/3345 7627
Fax: +55/67/3345 7630
azagatto@yahoo.com.br

Introduction

The critical power model is a simple non-invasive procedure that estimates aerobic endurance using a hyperbolic power-time relationship and other mathematical derivations [9,21,23,39,44,47,51] and it seems to represent the upper boundary of the heavy exercise intensity domain and the lower boundary of the severe intensity domain [13,24,25,41]. In addition, the critical power is considered similar to the highest work rate in which steady-state of oxygen uptake [37], lactate concentration [37,41,47], and acidic pH is achieved [37], although some authors consider that the intensity at critical power does not correspond to maximal lactate steady state [8,10]. Although the power-time and work-time relationships have been extensively used to determine the critical power in cycling exercise [5,8,23]; the relationships between velocity-time and distance-time have been named critical velocity and extended to running [6,41] and swimming [9,39,46,47]. The critical power concept has been adapted and used in intermittent efforts [26,33,35], allowing simulation of some motor patterns performed in intermittent sports [35].

In order to evaluate aerobic endurance using critical power model in a specific table tennis test, an intermittent sport with aerobic system predominance [50], Zagatto and colleagues [51] adapted the critical power model for critical frequency of effort, simulating offensive forehand strokes against balls from a ball throwing machine, considering effort intensity as throwing machine frequency (*f*), which was named critical frequency (*Cf*). These authors estimated the *Cf* considering the y-intercept of the linear frequency-inverse of time relationship (Lin–*f*) fitted using 3–4 exercise bouts performed until technical exhaustion. The exhaustion criterion considered was 4 consecutive stroke errors, which mostly included hitting the ball off the table, into the net and missing the ball [51]. The *Cf* values

obtained in this adaptation for table tennis showed results statistically similar and statistically correlated with intensities obtained in the aerobic-anaerobic transition (determined by intensity of second break point blood lactate curve) [31,51] and lactate minimum [31] tests. Additionally, during a continuous test at C*f*, a maximal dynamic equilibrium between blood lactate production and disappearance was seen [51].
The main limitation of the previous studies is that table tennis protocols were performed until technical and not maximum or voluntary exhaustion, which could lead to errors in C*f* determination [31,51]. Additionally, although these investigations described the C*f* as a good parameter to estimate the aerobic endurance, the authors determined [31,51] C*f* using only one of the 5 linear and nonlinear mathematical models. Another limitation is that C*f* was compared only with procedures that estimate the aerobic endurance using blood lactate responses (i.e., anaerobic threshold, lactate minimum, and lactate steady state tests) [31,51]. Probably the comparison of the C*f* with respiratory parameters such as peak oxygen uptake ($\dot{V}O_{2PEAK}$), intensity associated with $\dot{V}O_{2PEAK}$ ($f\dot{V}O_{2PEAK}$) and respiratory compensation point (RCP) may reinforce the use of C*f* as an aerobic parameter in table tennis. Thus, the main purposes of the present study were: i) to compare the critical power concept adapted for specific table tennis test (C*f*) estimated from exercise sessions performed until both voluntary and technical exhaustion; ii) to determine and to compare the C*f* estimated using 5 linear and nonlinear mathematical models; iii) to verify the relationship between the C*f* estimated from 5 mathematical models and compensation point (RCP), peak oxygen uptake ($\dot{V}O_{2PEAK}$) and minimal intensity at which $\dot{V}O_{2PEAK}$ was achieved ($f\dot{V}O_{2PEAK}$). Based on the studies with table tennis [31,51] and other ergometers [8,12,34] that found a significant association between critical power model and respiratory or ventilatory parameters, we hypothesized that the C*f* values estimated in table tennis will present statistical correlation with respiratory parameters, independent of exhaustion criteria and mathematical modeling. This study was conducted in 2 stages, the first one compared the C*f* values estimated from 2 exhaustion criteria (i.e., technical and voluntary) and from 5 mathematical models, and the second compared and correlated C*f* values with RCP, $\dot{V}O_{2PEAK}$, and $f\dot{V}O_{2PEAK}$.

Methods
▼
Subjects

9 national level male table tennis players [18(1) years; 62.3 (4.4) kg; and 172.1 (2.9) cm] participated in the study. The subjects had been engaged in regular systematic training in table tennis for at least 4 years. The athletes were familiarized with experimental procedures and equipments, and were instructed to keep to the same individual light meal at least 2 h before tests. In addition, they were instructed to maintain hydration habits, and to avoid additional sessions of hard physical activity and alcohol or caffeine ingestion during the experimental period. All procedures were approved by the University's Institutional Review Board for Human Subjects (Human Research Ethics Committee – Bioscience Institute protocol #2982) and were conducted in accordance with the Declaration of Helsinki and Ethical Standards in Sport and Exercise Science Research [18]. Athletes and their parents, if pertinent, were informed about experimental procedures and risks, and signed an informed consent prior to their participation in the study.

Procedures

Subjects completed the evaluation sessions in 10 days. The tests were carried out in specific table tennis tests using a ball throwing machine (Robopro Plus, Tibhar, Saarbruecken, Germany). The subjects performed a maximal incremental test and a critical frequency test (i.e., an adaptation of critical power test for table tennis) with a minimum interval of 24 h. In the 2 tests, the oxygen uptake ($\dot{V}O_2$) was measured by 3-breath average using a portable metabolic system (MedGraphics VO2000, Medical Graphics Corp., St. Paul, MN, USA). The gas analyzer was calibrated before each test following manufacturers' recommendations. In the C*f* test, blood samples were taken at 3rd, 5th and 7th min after exhaustion at each exercise bout to analyze the blood lactate using an electrochemical lactate analyzer (YSI 1500 SPORT, Yellow Springs Instruments, Yellow Springs, OH, USA). In all exercises strong verbal encouragement was provided.
The Tibhar RoboPro Plus (Tibhar, Saarbrücken, Germany) can be adjusted from 0 to 9 arbitrary units for ball-throwing frequency (f; ball·min^{-1}). On its standard frequency control, changing by one arbitrary unit results in an approximate frequency change of 10 balls·min^{-1}. Because of this, an alternative control unit was built, allowing a change in one arbitrary unit to correspond to one ball·min^{-1}. The Tibhar RoboPro Plus also has adjustments for ball speed and lateral ball oscillation, which were maintained constant and corresponded to setting 4 (i.e., 35 km·h^{-1}) and setting 5, respectively. The balls were systematically thrown aiming at 2 points on the table (30–40 cm either side of the table centre line – maximal equipment amplitude), so that the ball made contact with the table 50–60 cm from the net, simulating an opponent's shot. Only shot frequency (exercise intensity) was modified during the test by adjusting throwing frequency, according to the evaluation needed.

Maximal incremental test

The players performed a maximal incremental test to measure $\dot{V}O_{2PEAK}$, minimal exercise intensity (frequency) at which $\dot{V}O_{2PEAK}$ was achieved ($f\dot{V}O_{2PEAK}$) and the respiratory compensation point (RCP). The maximal incremental test consisted of initial frequency of 30 balls·min^{-1} with increments of 4 balls·min^{-1} every 2 min until voluntary exhaustion. The voluntary exhaustion was defined as the moment in which the subject decided to interrupt the test in spite of strong verbal enc ouragement. $\dot{V}O_{2PEAK}$ was considered as the highest average $\dot{V}O_2$ during the last 30 s, and $f\dot{V}O_{2PEAK}$ was considered as the minimum intensity at which $\dot{V}O_{2PEAK}$ was achieved. The RCP was considered as the point of increase of both ventilatory equivalents of O_2 ($\dot{V}_E/\dot{V}O_2$) and CO_2 ($\dot{V}_E/\dot{V}CO_2$) [14,16] (▶ **Fig. 1**).

Critical frequency test

The athletes performed 3–4 exercise bouts until exhaustion [31,51,52] with intensities applied randomly between 95 and 130% $f\dot{V}O_{2PEAK}$. 7 subjects performed 3 exercise bouts and 2 subjects performed 4 exercise bouts. The intensities were pre-chosen to result in exhaustion between 2 to 10 min [19,36]. The exercise bouts were separated by a minimum break of 2 h and no more than 2 repetitions were performed per day. Exercise time to exhaustion (*t*lim) was measured in each exercise bout. For

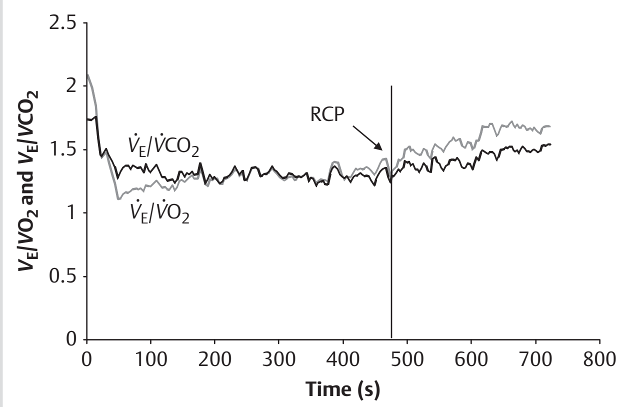

Fig. 1 Determination of respiratory compensation point (RCP) in one subject during maximal incremental test.

estimation of C*f*, 2 time to exhaustion (*t*lim) criteria were used: i) the technical exhaustion occurred after 4 consecutive errors in strokes [31,52] including hitting the ball off table, into the net and missing the ball; ii) voluntary exhaustion.

The C*f* was estimated from 5 mathematical models, where: *t*lim = time to exhaustion; *f* = ball throwing frequency; TB = total balls thrown [*t*lim × *f*]; f_{MAX} = maximum intensity where time is zero and *W′* = total amount of work that can be performed above the C*f*. The 5 mathematical models are shown below:

The linear frequency model is based upon the linear regression of *f* vs. the reciprocal *t*lim ($t\text{lim}^{-1}$) (Lin–*f*), where C*f* corresponded to y-intercept of regression line [31,51,52] (Eq. 1).

$$f = Cf + (W' \times t\text{lim}^{-1}) \qquad \text{(Lin–}f\text{) (Eq. 1).}$$

The second mathematical model was equivalent to the linear relationship between total balls thrown and *t*lim (Lin–TB), where C*f* corresponded to slope of regression line, adapted from Monod and Scherrer [30] (Eq. 2).

$$TB = W' + (Cf \times t\text{lim}) \qquad \text{(Lin–TB) (Eq. 2).}$$

The third mathematical model was a nonlinear model. This model is based upon the hyperbolic relationship between *f* and *t*lim and is described as a nonlinear 2-parameter model (Non–2), where C*f* corresponded to frequency asymptote of this relationship. This mathematical model was adapted from Monod and Scherrer [30] (Eq. 3).

$$t\text{lim} = W'/(f - Cf) \qquad \text{(Non–2) (Eq. 3).}$$

The fourth model was also nonlinear model, including the maximal effort intensity (f_{MAX}) as a parameter, which consists of the intensity where time = 0. This model was called nonlinear 3-parameter model (Non–3), adapted from Morton [32] (Eq. 4).

$$t\text{lim} = [W'/(f - Cf)] - [W'/(f_{MAX} - Cf)] \qquad \text{(Non–3) (Eq. 4).}$$

The fifth regression model was an exponential model (EXP) that also includes the f_{MAX} parameter, as well as an undefined time constant (τ). This mathematical model was adapted from Hopkins et al. [20] (Eq. 5).

$$f = Cf + (f_{MAX} - Cf) \times \exp^{(-t\text{lim}/\tau)} \qquad \text{(EXP) (Eq. 5).}$$

Table 1 Results of time until exhaustion (*t*lim) measured from technical and voluntary exhaustions criteria obtained in each exercise bout performed in the critical frequency test. Results are shown as mean (SEM).

	1st Bout	2nd Bout	3rd Bout	4th Bout
*t*lim (s)				
voluntary exhaustion	481.3 (76.1)	300.5 (26.7)	180.2 (30.9)	131.4 (22.9)
technical exhaustion	431.1 (40.0)	294.3 (27.0)	180.2 (30.9)	127.8 (24.4)

Statistical analysis

The 5 mathematical models used to estimate C*f* were applied using STATISTICS 7.0 software (Statsoft, Tulsa, OK, USA). Results are shown as means (± standard error of mean). Initially, the Shapiro-Wilk's test was used to analyze variable normality. This analyses showed that all scores were normals. The paired t-test was used to analyze significant differences between *t*lim values from technical and voluntary exhaustion criteria. 2-way repeated measures analysis of variance (ANOVA) was used to analyze significant differences between C*f* values from 5 mathematical models using technical and voluntary exhaustion criteria. In the second stage, one way repeated measures ANOVA was used to analyze significant differences among each estimated C*f* and RCP, and between $\dot{V}O_{2PEAK}$ and $\dot{V}O_2$ values obtained in each exercise session of the C*f* test. If necessary, the ANOVA tests were followed by post-hoc comparison using the Newman-Keuls procedure. The intraclass correlation test (ICC; 2-way random model, consistency option, single score) was used to compare C*f* estimated from mathematical models and exhaustion criteria. Pearson product-moment correlation coefficients were used to analyze correlation among C*f* s and RCP, $\dot{V}O_{2PEAK}$ and $f\dot{V}O_{2PEAK}$. In all cases, statistical significance was set at $P < 0.05$.

Results

▼

The $\dot{V}O_{2PEAK}$ of maximal incremental test was 49.8 (1.1) $ml \cdot kg^{-1} \cdot min^{-1}$ and the $f\dot{V}O_{2PEAK}$ was 56.7 (3.4) $balls \cdot min^{-1}$. Added to the values found in maximal incremental test at the point of exhaustion, the pulmonary ventilation was 75.0 (5.0) L, heart rate was 193 (3.4) bpm and the respiratory exchange ratio was 1.12 (0.03).

The 4 exercise bouts applied randomly in the C*f* test were 95.9 (3.1) % [57.7 (4.6) $balls \cdot min^{-1}$], 107.0 (2.2) % [60.6 (3.7) $balls \cdot min^{-1}$], 116.7 (1.9) % [66.2 (4.2) $balls \cdot min^{-1}$], and 126.7 (2.7) % [68.2 (3.6) $balls \cdot min^{-1}$] $f\dot{V}O_{2PEAK}$. The *t*lim values from technical and voluntary exhaustion criteria in each exercise session were not different (▶ **Table 1**). There was no significant difference between $\dot{V}O_{2PEAK}$ [49.8 (1.1) $ml \cdot kg^{-1} \cdot min^{-1}$] and the $\dot{V}O_2$ values obtained in the 4 exercise bouts ($P = 0.24$; $F = 1.51$), which corresponded to 43.3 (1.9) $ml \cdot kg^{-1} \cdot min^{-1}$ [87.8 (1.5)% $\dot{V}O_{2PEAK}$], 46.0 (1.0) $ml \cdot kg^{-1} \cdot min^{-1}$ [92.6 (1.6) % $\dot{V}O_{2PEAK}$], 47.3 (1.1) $ml \cdot kg^{-1} \cdot min^{-1}$ [95.0 (2.8)% $\dot{V}O_{2PEAK}$], and 47.8 (2.2) $ml \cdot kg^{-1} \cdot min^{-1}$ [95.8 (4.7)% $\dot{V}O_{2PEAK}$] respectively. As an example, $\dot{V}O_2$ responses of Subject 2 in the 4 exercise bouts performed in the C*f* test are shown in ▶ **Fig. 2**. In addition, blood lactate values in these exercise sessions were not different ($P = 0.19$; $F = 3.08$) and corresponded to 6.0 (0.5) $mmol \cdot L^{-1}$, 7.4 (0.9) $mmol \cdot L^{-1}$, 7.4 (0.8) $mmol \cdot L^{-1}$, and 5.5 (0.4) $mmol \cdot L^{-1}$, respectively. The C*f* values from 5 mathematical models estimated using 2 exhaustion criteria are shown in ▶ **Table 2**. In the Non–3 model, C*f* could be

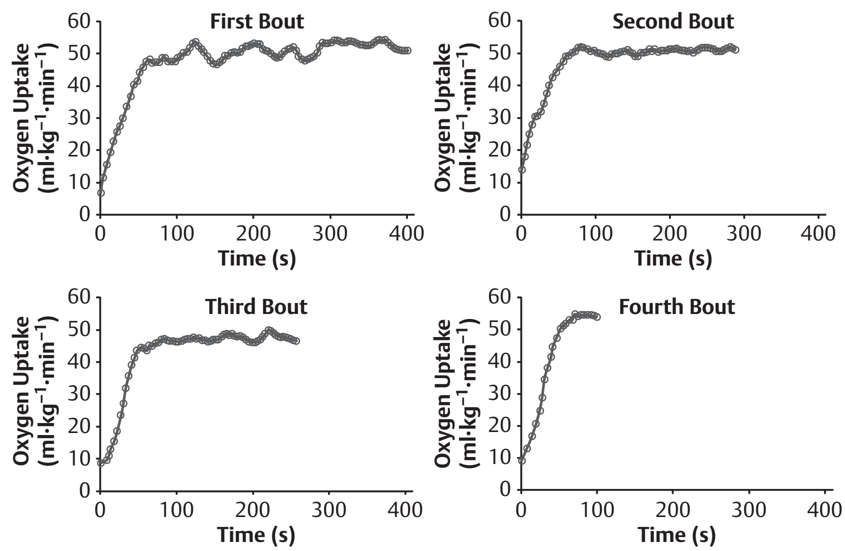

Fig. 2 Oxygen uptake behavior in each exercise session in the critical frequency test. Data correspond to Subject 2.

Table 2 Values of *Cf* estimated from 4 mathematical models, *Cf* intensities relative at $f\dot{V}O_{2PEAK}$ (% at $f\dot{V}O_{2PEAK}$), goodness of fit (R^2), and standard errors of *Cf* estimation (SE).

	Cf (balls · min^{-1})	% at $f\dot{V}O_{2PEAK}$ (%)	Goodness of fit (R^2)	SE (balls · min^{-1})
voluntary exhaustion				
Lin–*f* (*n* = 9)	53.5 (3.6)*	94.5 (3.5)	0.945 (0.018)	2.0 (0.5)
Lin–TB (*n* = 9)	52.2 (3.5)*	92.3 (3.8)	0.996 (0.006)	2.2 (0.5)
Non–2 (*n* = 9)	50.3 (3.6)	89.2 (4.6)	0.954 (0.016)	2.3 (0.8)
Non–3 (*n* = 6)	45.2 (7.0)	80.2 (10.1)	0.995 (0.005)	4.2 (4.2)
technical exhaustion				
Lin–*f* (*n* = 9)	53.5 (3.5)*	94.5 (3.5)	0.947 (0.016)	2.0 (0.5)
Lin–TB (*n* = 9)	52.2 (3.5)*	92.3 (3.7)	0.995 (0.008)	2.3 (0.6)
Non–2 (*n* = 9)	50.2 (3.5)*	89.2 (4.6)	0.952 (0.016)	2.4 (0.8)
Non–3 (*n* = 7)	43.2 (5.6)	78.2 (10.1)	0.978 (0.018)	4.4 (3.8)

* $P<0.05$ in relation at *Cf* estimated from Non–3

Table 3 Intraclass correlation coefficients obtained between *Cf* intensities estimated from 4 mathematical models which were determined using time until exhaustion identified by voluntary exhaustion and technical exhaustion. The correlation coefficients are shown corresponding to voluntary exhaustion and the values in brackets corresponding to technical exhaustion.

	Cf		
	Lin–*f*	Lin–TB	Non–2
Cf	–	–	–
Lin–*f*	–	–	–
Lin–TB	0.99*(0.99*)	–	–
Non–2	0.96*(0.96*)	0.98*(0.98*)	–
Non–3	0.79*(0.73*)	0.80*(0.75*)	0.81*(0.75*)

* $P<0.05$

estimated for 6 subjects using voluntary exhaustion (~67% success rate) and for 7 subjects using technical exhaustion (~78% success rate). In the EXP model, *Cf* was only estimated for 3 athletes for both exhaustion criteria (~33% success rate), and due to this low sample rate (*n*), this method was excluded from the study. The *Cf* estimated from 4 models using voluntary exhaustion and technical exhaustion were not different and were significantly correlated [ICC = 0.99 (0.01); range 1.00–0.97]. However, the *Cf* obtained from Non–3 model was significantly lower than verified in Lin–*f* and Lin–TB with voluntary exhaustion and lower than the other 3 mathematical models with technical exhaustion (Lin–*f*, Lin–TB, and Non–2 models; $P<0.00$; $F=9.97$). In addition, *Cf* estimated from 4 models were significantly correlated (**Table 3**).

As the different exhaustion criteria did not affect *Cf* estimates, only technical exhaustion *Cf* values were used in the second stage of the study. RCP corresponded to 47.4 (3.4) balls · min^{-1} [81.9 (3.4) % $f\dot{V}O_{2PEAK}$] and one-way ANOVA did not find a significant difference between RCP and each estimated *Cf*, whereas Non–3 was significantly lower than Lin–*f* and Lin–TB (result obtained previously using 2-way ANOVA in the first stage of the study). In addition, RCP was statistically correlated with *Cf* estimated from Lin–*f* and Lin–TB (**Fig. 3**), and $f\dot{V}O_{2PEAK}$ was significantly correlated with Lin–*f*, Lin–TB, and Non–2 (**Fig. 4**). However, there was no significant correlation between any *Cf* and $\dot{V}O_{2PEAK}$ (**Fig. 5**).

Discussion

In this study, the goodness of fit values (determination coefficient; R^2) for the 5 mathematical models used to estimate *Cf* ranged from 0.945 to 0.996 independent of exhaustion criteria. The combination of these results with the corresponding low standard errors (SE) (**Table 2**) show the consistency of the mathematical models used to estimate *Cf*. However, *Cf* could not be estimated for all subjects using the Non–3 (success rate of ~67% from voluntary exhaustion and ~78% from technical exhaustion) and EXP models (success rate of 33%). Due to the low success rate, the *Cf* values from EXP model were excluded from the study.

The first stage of this work investigated the effects of the exhaustion criteria and the use of mathematical models on *Cf* estima-

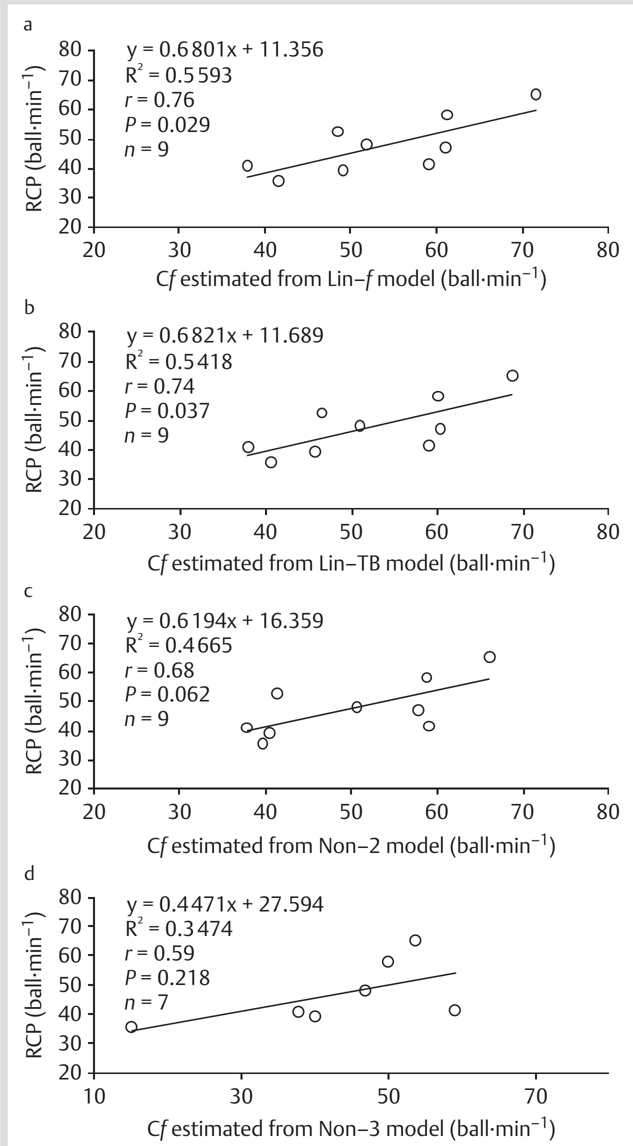

Fig. 3 Relationship between respiratory compensation point (RCP) and *Cf* estimated from Lin–*f* (**a**), Lin–TB (**b**), Non–2 (**c**) and Non–3 (**d**) mathematical models.

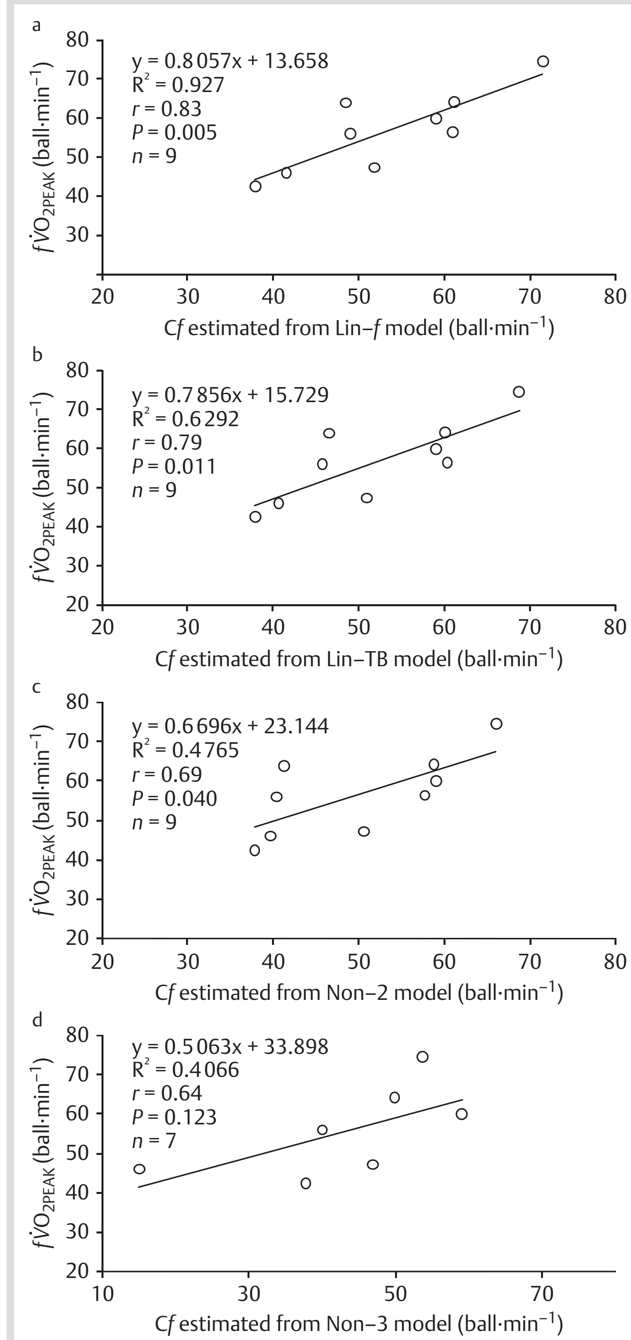

Fig. 4 Relationship between minimum intensity at which $\dot{V}O_{2PEAK}$ was achieved ($f\dot{V}O_{2PEAK}$) and *Cf* estimated from Lin–*f* (**a**), Lin–TB (**b**), Non–2 (**c**) and Non–3 (**d**) mathematical models.

tion. The critical power concept is supported by the hyperbolic relationship between intensity and time to exhaustion [30]. However, the adaptation of the critical power concept for table tennis has been applied with exercises performed until technical exhaustion [31, 51, 52] but not by voluntary exhaustion as applied in other ergometers [5, 6, 8, 21, 23, 34]. The use of technical criterion as exhaustion could result in errors in the mathematical relationships used for estimating *Cf*. Our results showed that technical exhaustion in table tennis occurs statistically at the same moment as voluntary exhaustion, allowing technical exhaustion to be used as the exhaustion criterion in the specific table tennis test, as previously used by Zagatto et al. [51] and Morel and Zagatto [31].

In relation to mathematical modeling in the specific table tennis test, the *Cf* values could only be estimated for ~33 % of subjects using the EXP model, and for 67 % (voluntary exhaustion) and 78 % (technical exhaustion) of subjects using the Non–3 model. *Cf* estimated from the Non–3 model was statistically lower than the other models (Lin–*f*, Lin–TB, and Non–2). The influence of mathematical modeling in critical power or critical velocity calculations have been described by Bull et al. [5], Gaesser et al. [12], and Morton [32], where results can vary by up to 24 % [5]. Similar to our results, other authors have found the lowest critical power and critical velocity values in the Non–3 model [4–6, 12, 21, 32]. Bull et al. [6] explained that including maximum intensity in the Non–3 model resulted in lower critical power values and increased SE's; this can also be seen in our results (▶ **Table 2**). However, for table tennis, all *Cf* values that were obtained from different mathematical models showed significant correlations (▶ **Table 3**).

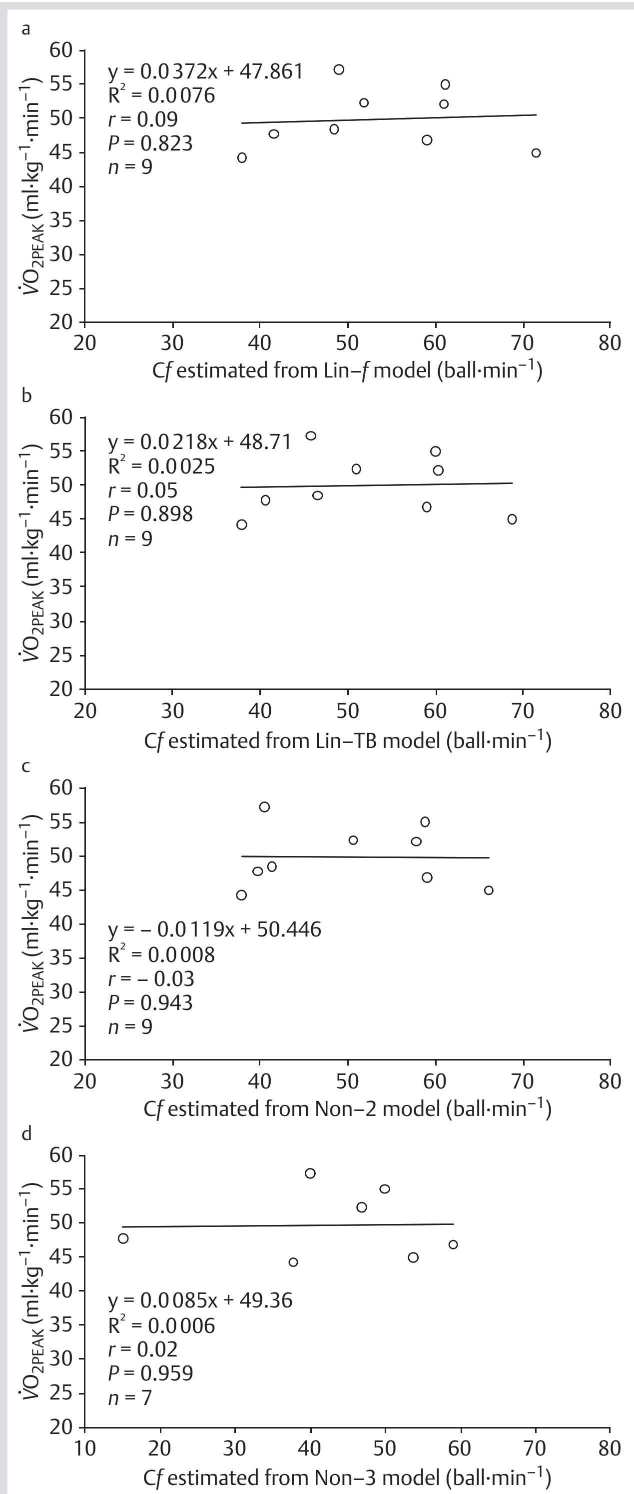

Fig. 5 Relationship between peak oxygen uptake ($\dot{V}O_{2PEAK}$) and *Cf* estimated from Lin–*f* (**a**), Lin–TB (**b**), Non–2 (**5**) and Non–3 (**d**) mathematical models.

Nevertheless, the critical frequency test applied in the present study showed some limitations. First, the highest intensity in the *Cf* test [68.2 (3.6) balls·min^{-1}; 127.7 (2.7) % $f\dot{V}O_{2PEAK}$] resulted in a *t*lim of approximately 130 s. This intensity was prechosen before the beginning of exercises to obtain a *t*lim of approximately 120 s, the lowest *t*lim recommended by Hill [19]. A *t*lim between 2 and 10 min is considered the ideal range for hyperbolic and linear mathematical models [19,36], but for better critical power results in the 3-parameter and exponential models, the highest intensity is better [32]. However in a pilot study, we attempted to apply a higher exercise intensity to reduce *t*lim, but players were unable to perform this exercise session. Another limitation of the study was the application of only 3–4 exercise bouts in the critical frequency test. The low number of exercise bouts should allow for the estimation of aerobic parameter using the 2 parameter modeling; on the other hand, to use the exponential and 3-parameter nonlinear models requires more than 3 exercise sessions. However, the application of the critical frequency test with a higher number of exercise sessions could hinder practical application in routine training of sports.

The second aim of this study was compare C*f* and RCP intensities, and to correlate each C*f* estimated with RCP, $f\dot{V}O_{2PEAK}$, and $\dot{V}O_{2PEAK}$. RCP was identified as the intensity at which $\dot{V}_E/\dot{V}CO_2$ increased, and it represents the point at which hyperventilation occurs from excessive acidosis [48]. Some authors call this intensity the second ventilatory threshold [8,29], and it has been significantly correlated with endurance capacity [1,11,12,22,29,38]. In the present study, the RCP intensity was not statistically different from C*f* estimated from 4 mathematical models and it was significantly correlated with C*f* estimated from Lin–*f* (**Fig. 3a**) and Lin–TB (**Fig. 3b**) models. Dekerle et al. [8] did not find significant differences between critical power and second ventilatory threshold during exercise on a cycloergometer, but they were higher than maximal lactate steady state intensity. Similar to our results, Gaesser et al. [12] found significant correlations between ventilatory threshold and critical power estimated from 5 models in cycling (*r* from 0.69 to 0.91), but the ventilatory threshold (considered as the highest power output that could be maintained for 40 min without a significant rise in ventilation after 20th min) was statistically lower than critical power, except in the Non–3 model. Nakamura et al. [34] recently found a significant correlation between critical power and second ventilatory threshold (*r*=0.86) on a cycloergometer. Other important significant correlations were found between $f\dot{V}O_{2PEAK}$ and C*f* estimated from Lin–*f* (**Fig. 4a**), Lin–TB (**Fig. 4b**) and Non–2 (**Fig. 4c**) models. Billat and Koralsztein [2] and Billat et al. [3] considered intensity associated with $\dot{V}O_{2PEAK}$ a good endurance index, and it has also been correlated with maximal aerobic power and movement economy [7]. Thus, in general, the significant correlations found between C*f* estimated from linear and nonlinear 2-parameter models with RCP and $f\dot{V}O_{2PEAK}$ show evidence that critical frequency intensity can estimate the aerobic component. Our results, and those by Zagatto et al. [51] and Morel and Zagatto [31] reinforce the assumption that C*f*, in table tennis, corresponds to the exercise intensity at maximal steady state and aerobic-anaerobic transition due to present values statistically similar and statistically correlated to RCP, lactate minimum [31] and anaerobic threshold (i.e., intensity of second break point blood lactate curve) [31,51], and also a maximal dynamic equilibrium occurs between blood lactate production and disappearance during continuous exercise at C*f* [51]. The assumption that at critical power intensity and derivations (i.e., critical velocity and other) correspond to a maximal steady state are also supported by findings of Poole et al. [37], who demonstrated that blood lactate, pH and bicarbonate attained a steady state during prolonged exercise at critical power; and also by studies that assume that the critical power corresponds to maximal lactate steady state [41,47,51]. In a recent review, Jones et al. [25] described that there is evidence that the critical power corresponds to the highest power output that can be sustained without a progressive loss of homeostasis and it occurs at a similar intensity to maximal lactate steady state. However, there are some studies that described that the intensity at critical power does not represent the intensity at maximal lactate steady state [8, 10].

There was no significant correlation between C*f* and $\dot{V}O_{2PEAK}$. During maximum incremental test the increment of intensity was performed by rise of shot frequency, which represents mostly increase in internal power, which is defined as the energy changes of moving body segments [17, 28, 42]. The increase of internal power occurs due mostly to a rise in contraction velocity in the exercising muscle, and similarly occurs during cycling exercise, and probably the increase of the internal power increases the oxygen cost and decreases the muscular efficiency during exercise [17, 28, 42] through a combination of physiological, biomechanical and neuromuscular phenomena [42]. Despite the fact that exercises with high internal power lead to a higher cost of energy compared to exercises with lower internal power, during specific table tennis tests the contraction velocity in the active muscles attain high values that are not sufficient to achieve the maximal physiological response. The decrease in muscle efficiency may perhaps lead to precocious fatigue and influence the performing of the exercise with ideal stroke techniques. Girard and Millet [15] described that during intense efforts in racket sports (i.e., repeated intense strokes) a precocious neuromuscular fatigue can occur caused by very short recovery periods between each stroke, originated from alterations in excitation-contraction coupling and/or reduction in sarcolemmal excitability because of ionic disturbances and, consequently, this fatigue can contribute to a non-achievement of maximal oxygen uptake. This limitation to achieve maximal effort during incremental protocols in racket sport was also observed by Smekal et al. [40] who found lower $\dot{V}O_{2PEAK}$ values in a specific tennis test compared to treadmill test.

Table tennis is a highly complex sport, which requires a unique combination of technical skills (motor), physical fitness, and physiological factors [27, 43], and analysis of only the forehand stroke is a limitation of this study. However, studies have shown forehand stroke analysis useful for measuring physiological responses during the systematically performed exercise, but respecting the specificity of table tennis. In opposition to exercise specificity, some researchers have measured aerobic fitness in specific racket sport tests just using simulated running movements on court, and not using effective strokes [14, 16, 49]. Thus our method presents a significant advance in this area of study. The application of C*f* test allows the estimation of aerobic endurance using a non-invasive and easy application procedure that allows the use of the same movements and motor patterns of table tennis, respects the sport's specificity and increases the ecological validity of the test. These aspects allow the use of C*f* in routine table tennis training.

In addition to the linear and nonlinear mathematical models, Vanhanhalo et al. [45] suggested to determine the critical power using the 3-min all-out cycling test. However, the linear intensity-inverse of *t*lim relationship has been well adapted for table tennis specific test [31, 51, 52] and can be estimated using few data points. Wakayoshi et al. [47] described that critical velocity in swimming can be estimated from linear distance-time relationship using only 2 data points. Although it is possible to estimate the critical power using few data points by linear and hyperbolic mathematical models, the use of few data points to estimate critical power from 3-parameters and exponential models can be limited. In summary, based on the recent findings related to the critical power model adapted for table tennis, we can consider that Lin–*f* and Lin–TB mathematical models presented better results based mostly on the relationships with RCP and $f\dot{V}O_{2PEAK}$. Additionally, based on results found by Zagatto et al. [51] and Morel and Zagatto [31], which present values of the C*f* estimated from Lin–*f* model statistically similar and statistically correlated with intensities obtained at the anaerobic threshold [31, 51] and lactate minimum [31] and besides represent the maximal dynamic equilibrium between blood lactate production and disappearance, we can recommend the use of Lin–*f* mathematical model for estimating the aerobic endurance in specific table tennis test.

Conclusion

The critical power concept adapted for table tennis was not affected by technical or voluntary exhaustion criteria. However, the EXP model did not show a good fit for table tennis and the Non–3 model intensity was significantly lower than other models. Finally, C*f* estimated from 2 linear models and from Non–2 model was not statistically different from the intensity RCP. These aerobic parameters also showed a significant correlation in between each other and also with RCP and $f\dot{V}O_{2PEAK}$ intensities, indicating that the C*f* from these models (2 linear and non-linear 2 parameters models) can be used to estimate the specific aerobic endurance in table tennis tests.

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