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Fatigue thresholds as a marker for transition from aerobic-to--anaerobic exercise intensity in intermittent sport players: an electrophysiological study

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Abstract

Introduction. **In recent years, there have been contradictions regarding the fatigue thresholds denoting the boundary between heavy and severe exercise domain as the marker for transition from aerobic-to-anaerobic exercise intensity.** Aim of Study. **This study aims to examine the various fatigue thresholds (critical power, respiratory compensation point and neuromuscular fatigue threshold) as marker for transition from aerobic-to--anaerobic exercise intensity in intermittent sport players based on the VO_2 kinetics, muscle activations and mathematically derived models.** Material and Methods. **Thirteen male intermittent sport players (age = 21.30 ± 2.52 years; height = 164.76 ± 6.2 cm; weight = 57.03 ± 4.93 kg; BMI = 21.01 ± 1.41 kg/m^2) were recruited for this study. The participants performed total 11 sessions, one incremental test for evaluating electromyographic fatigue threshold (EMGFT), four time-to-exhaustion trials for evaluating critical power with mathematical models (CP) and two verification trials, four constant load tests for evaluating critical power based on VO_2 kinetics (CP') and respiratory compensation point (RCP).** Results. **The Bland–Altman analysis revealed that CP was not in agreement with CP' (r^2 = 0.89, $p < 0.00$; t = 9.70, Cohen's f = 0.99). Also, VO_2 corresponding to the work rates of CP was significantly different from the CP' and RCP ($p < 0.001$). However, work rates corresponding to the CP' were not significantly different and in agreement to the work rates corresponding to RCP (t = –1.65, p = 0.062; r^2 = 0.61, p = 0.66, t = –4.18, Cohen's f = 1.26) and EMGFT (t = –0.633, p = 0.269; r^2 = 0.43, p = 0.342, t = –4.18, Cohen's f = 0.99), respectively.** Conclusions. **The CP', EMGFT and RCP corresponds to similar work rates and can depict the boundary between heavy to severe exercise domains which could be used for performance testing and training the intermittent sport players.**

KEYWORDS: VO_{2max}, exercise domains, critical power, respiratory compensation point, EMG fatigue threshold.

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Introduction

According to the principle of specificity of training, adaptations and performance efficiency are based on exercise intensity or domains, in which the sportsperson is trained [15]. The frequently used classification of the exercise domains is moderate, heavy, severe and extreme domains [23]. The transition of exercise from one domain to the other is highly studied as distinct aerobic and anaerobic thresholds. The transition between the heavy--to-severe domain is denoted as the anaerobic threshold or fatigue threshold, which can distinguish between the "fatiguing" and "non-fatiguing" work rates [8]. In recent years, there have been several debates concerning the transition from heavy-to-severe or aerobic-to--anaerobic exercise, as well as the methods of evaluating this transition. This article aims to explore the anaerobic/fatigue thresholds as markers for testing and training in intermittent sport players because these players spend a significant period of time within the severe-intensity domain, therefore, these anaerobic thresholds become very important when determining the intensity of training protocols and monitoring their improvements.

Critical power is considered as the metabolic steady state widely accepted as a boundary between the heavy and severe exercise domain. Metabolically, critical power represents the limit of the sustainable rate of oxidative metabolism. According to the VO_2 kinetics, it is the highest exercise intensity where exercising VO_2 can be stabilized before reaching VO_{2peak} [8, 12, 25] (denoted as CP' for reference of this article). Based on mathematical models, critical power is explained by the relationship between power output and time to exhaustion. This duration follows a hyperbolic function of output power versus time, where the asymptote represents critical power, whereas the curvature constant (W') corresponds to the finite amount of work that can be consumed on critical power [19, 25]. Critical power is usually evaluated using various mathematical models (denoted as CP, for the purpose of this article) by performing three or more time-to-exhaustion trials [7, 25]. However, whether a true maximal metabolic steady state representing critical power can be evaluated by the mathematical models or not, is still controversial [7]. A recent meta-analysis also suggested that between critical power and other indices of physiological function, critical power (if evaluated correctly) represents a unique work rate as it constitutes the maximal metabolic steady-state, which other ventilatory and metabolic thresholds are unlikely to represent [9]. Studies have found a contradiction that exercising VO_2 might not always attain VO_{2peak} even if the work rate exceeded mathematically evaluated critical power (CP) [3].

Electromyographic fatigue threshold (EMGFT) is the exercise intensity an individual can maintain indefinitely without the need to recruit more motor units and hence depicts the neuromuscular fatigue threshold. EMGFT represents an EMG amplitude without trend, slope, or rate of change [18]. EMGFT has also been proposed and utilized as a reliable correlate of anaerobic and critical thresholds [8, 18]. Respiratory compensation point (RCP) is the maximum workload that can be sustained before metabolic acidosis causes hyperventilation [4, 14]. Some authors propose that RCP resembles the same workload as other markers of the aerobic-to-anaerobic transition. Moreover, in a recent series of investigations Broxterman et al. [4] and Ozkaya et al. [21] reported a high degree of intraindividual variability between CP and RCP and the difference between CP and RCP may question interchangeability of these phenomena [16]. To the best of our knowledge, no other study has ever investigated all the fatigue thresholds jointly on the same group of subjects. The authors aim to investigate and appraise the method to estimate critical power and to examine whether critical power, EMGFT and RCP represent the transition from heavy-to-severe or aerobic-to-anaerobic exercise domains and can be markers for testing and training in intermittent sport players. For this study, the authors hypothesized that RCP and EMGFT would not be statistically different from critical power.

Material and Methods

Participants

Thirteen (age = 21.30 ± 2.52 years; height = 164.76 ± ± 6.2 cm; weight = 57.03 ± 4.93kg; BMI = 21.01 ± ± 1.41 kg/m^2) trained national-level male intermittent sport players (football players, n = 13; hockey players, n = 8) participated in this study, determined according to the power analysis conducted with G*Power 3.1.9.2 for a power of 0.95 and the effect size of 0.8 and an α set at a priori of 0.05. The players had at least 4 years of training with an absence of lower limb injury in the last six months. Exclusion criteria specified individuals who were >18 years old, had a history of health-related concerns (e.g., cardiovascular, pulmonary, metabolic, muscular or coronary, etc.), or a positive physical activity readiness questionnaire (PAR-Q).

Compliance with ethical standards

The study was approved by the Institutional Ethics Committee of the university (details provided). The aims, methodology, and potential risks associated with the study were described to the participants. The participants signed an informed consent form that explained their rights as research participants. The research protocols were carried out according to the Declaration of Helsinki, 1964, its later amendments and also in accordance with Harris et al. [11].

Procedure

Before the maximal bout, the subject's body mass (via balance beam scale) and height (via stadiometer) were recorded. Subjects were fitted for their optimal seat height on the inertially braked cycle ergometer by aligning the seat at the level of the participant's iliac crest. Participants in this study completed 11 sessions at the same time assigned to report to the laboratory (to ensure no interactions with the effect of circadian fluctuations) with at least 24 hours in between.

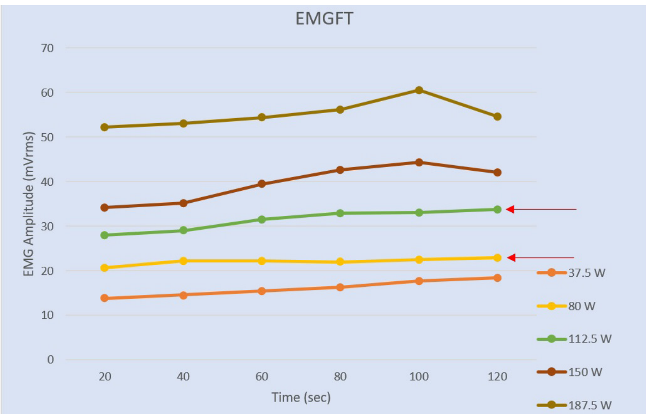
Outcome measures

Incremental tests for RCP and EMGFT

The subjects were instructed to warm up for 15 minutes before the incremental test, and then they were instructed to take a 10-minute break. Pulmonary gas exchange variables [minute ventilation (VE), VO_2, and VCO_2, maximal oxygen consumption (VO_{2max})] were measured breath by breath via an open circuit metabolic system (Powerlab/8M Metabolic System, ADInstruments Pty Ltd, Castle Hill, Australia) using Lab Chart software (version-8, ADInstruments Pty Ltd) sampling at 1000 Hz, and were later analysed as 10-second epochs. Heart rate and rhythm were monitored continuously during all tests via a heart rate monitor (Polar RS800, Polar Electro Oy, Kempele, Finland).

The DelSysTrigno™ Wireless EMG device (Delsys Inc., Boston, USA) was used to detect surface EMG activity through the surface EMG signal during the incremental test of the vastus lateralis muscles of the right lower limb. According to the SENIAM recommendations, Trigno sensors (Trigno Lab System; DelSys Inc., Boston, USA), consisting of two dry bar electrodes spaced 10 mm apart, were positioned in the middle of the muscle belly and aligned in the direction of the muscle fibres. The LabChart software was used to store the EMG signals with a band-pass filter (10–500 Hz), a sampling frequency of 1000 Hz, and also to assess the speed of the cycle ergometer. Each participant's initial power in the incremental test was set at 25 watts (W) with an increment of 25 W every 2 minute until the participant reached volitional exhaustion [10, 14].

Throughout the test, the individual kept a consistent pedal cadence of 70 revolutions per minute (rpm). When the subject failed to sustain a pedalling rate of 60 rpm despite significant verbal encouragement, the incremental test was stopped. The greatest 30-second



Note: mVrms – millivolt root mean square, W – watts, EMGFT – EMG fatigue threshold

Figure 1. Representative results for a participant for EMG fatigue threshold (EMGFT). Linear regression was performed for the EMG amplitude vs time relationship for each power output. The red arrow denotes the first significant result

VO_2 value obtained during the incremental test was considered the VO_{2max}. All the three authors blindly and separately determined RCP by evaluating VE/VCO_2 plotted against VO_2 and located the second breakpoint in the VE to VO_2 relation [12]. The procedure described by Galen et al. [10] was used to analyze recorded EMG signals to determine EMGFT (Figure 1).

Critical power based on mathematical assumptions (CP)

Data from four exhaustive tests lasting 2-10 minutes were applied to calculate CP in widely used equations from the mathematical model using nonlinear total work (Equation 1), linear total work (Equation 2), and linear 1/time (Equation 3) equations. Subjects underwent these four exams on different days in random order. To capture the VO_2 response to the mathematically assessed CP, 2 additional verification sessions (+15 W) were conducted. The termination criteria were identical as for the incremental test.

$$t = W'/(P - CP) \qquad \text{(Equation 1)}$$

$$W = W' + (CP \times t) \qquad \text{(Equation 2)}$$

$$P = CP + (W' \times \frac{1}{t}) \qquad \text{(Equation 3)}$$

Critical power by constant-load tests (CP')

CP' was the physiologically attained work rate corresponding to a slightly lower power output than the lowest work rate giving $VO_{2peak.}$ Four constant-load exercises performed on several days yielded individual power outputs corresponding to CP'. The value of CP' was calculated using the 95% threshold [22], i.e., the lowest work rate, at which the 30-second VO_2 mean data were closer than 95% to VO_{2max}. At +15 W intervals, the individual power outputs associated with CP' were recorded. The termination criteria were the same as for the incremental test.

Statistical analysis

Data are presented as means and standard deviation (SD). To ascertain if the data were normally distributed, the Shapiro–Wilk test was used. One-way repeated measures analysis of variance was performed to evaluate differences across variables and the least significant difference was employed as a post hoc test. Two sample means were compared using a paired-sample t-test. The limits of agreement between CP, CP', RCP, and EMGFT were determined using the Bland–Altman analysis (mean of differences ± 1.96 SD). The one-sample t-test was used to assess bias values of the variables to determine whether they differed substantially from zero ($p < 0.05$). Regression r^2 values were used to analyse the effect size (ES). ES of Cohen's f were categorized as no effect (>0.01), small effect (0.01-0.24), medium effect (0.25--0.39), and large effect (<0.40) [20]. Results with $p < 0.05$ were considered statistically significant. Results were evaluated using SPSS 21.0 (SPSS, Inc., Chicago, IL).

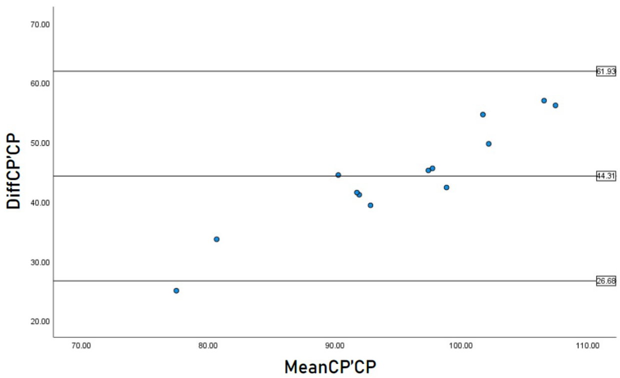
Results

The baseline data of the subjects was found to be normally distributed (Table 1). As a result of repeated measure analysis of variance, the work rates were found to be significantly different from one another ($p < 0.001$). Meanwhile, the interpretation of the paired t-test showed that the work rates corresponding to CP were significantly different from the work rates corresponding to CP' ($t = 17.77$; $p < 0.001$), RCP ($t = –17.113$; $p < 0.001$) and EMGFT ($t = –18.61$; $p < 0.001$). However, work rates corresponding to CP' were not different from the work rates corresponding to RCP ($t = –1.65$; $p = 0.062$) and EMGFT ($t = –0.633$; $p = 0.269$). Also, VO_2 corresponding to the work rates of CP was significantly different from CP' and RCP ($p < 0.001$). Following the Bland–Altman analysis, CP work rates (72.95 ± 4.94 W) were found to be significantly lower than the CP' work rates (117.26 ± ± 13.32 W). Results also indicated that there was low agreement between the work rates corresponding to CP and CP' ($r^2 = 0.89$, $p < 0.001$, $t = 9.70$, Cohen's f = 0.99), RCP (115.63 ± 13.32W; $r^2 = 0.88$, $p < 0.001$, $t = 8.7$, Cohen's f = 2.7) or EMGFT (118.28 ± 12.58W; $r^2 = 0.56$, $p = 0.037$, $t = –1.151$, Cohen's f = 1.12) (Bland–Altman plots are illustrated in Figures 2, 3 and 4, respectively), whereas there was a high agreement between CP' and RCP ($r^2 = 0.61$, $p = 0.66$, $t = –4.18$, Cohen's f = 1.26) and EMGFT ($r^2 = 0.43$, $p = 0.342$, $t = –4.18$, Cohen's f = 0.99) and also between RCP and EMGFT ($r^2 = 0.47$, $p = 0.735$, $t = 9.6$, Cohen's f = 0.86). Limits of agreement and bias values for exercise intensities in watts and results of one sample t-test between CP and the other performance indices are presented in Table 2.

Table 1. Descriptive and baseline data of the athletes

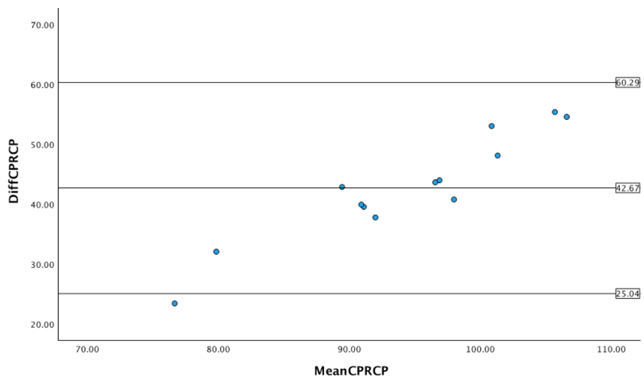
Variable	Mean	± SD
Age (years)	21.30	2.52
Height (cm)	164.76	6.2
Weight (kg)	57.03	4.93
BMI (kg/m)	21.01	1.41
VO_2 resting (ml/kg/min)	3.61	0.23
VO_{2max} (l/min)	3.66	0.27
CP' (W)	117.26	13.32
VO_2 at CP' (l/min)	3.37	0.27
CP (W)	72.95	4.9
VO_2 at CP (l/min)	2.97	0.27
RCP (W)	115.63	13.32
VO_2 at RCP (l/min)	3.31	0.29
EMGFT (W)	118.28	12.58

Note: BMI – body mass index, VO_2 – oxygen consumption, VO_{2max} – maximal oxygen consumption, CP' – critical power based on VO_2 kinetics, CP – critical power based on mathematical models, RCP – respiratory compensation point, EMGFT – EMG fatigue threshold, SD – standard deviation
Data are presented as means and SD.



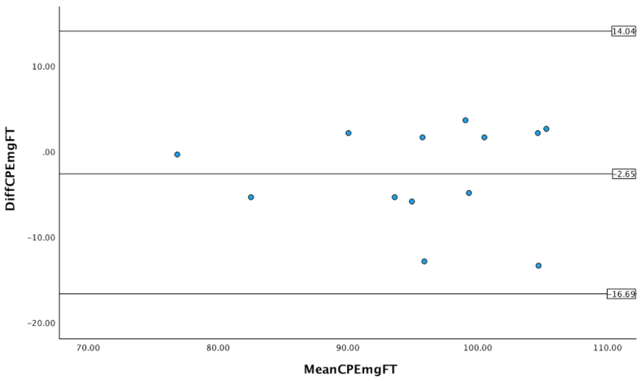
Note: CP – critical power by mathematical models, CP' – critical power by constant load tests, X axis – mean of CP and CP', Y axis – mean difference between CP and CP'

Figure 2. Limits of agreement between CP and CP' (±1.96 SD). The middle solid line represents the mean bias



Note: CP – critical power, RCP – respiratory compensation point, X axis – mean of CP and RCP', Y axis – mean difference between CP and RCP

Figure 3. Limits of agreement between CP and RCP (±1.96 SD). The middle solid line represents the mean bias



Note: CP – critical power, EMGFT – EMG fatigue threshold, X axis – mean of CP and EMGFT, Y axis – mean difference between CP and EMGFT

Figure 4. Limits of agreement between CP and EMGFT (±1.96 SD). The middle solid line represents the mean bias

Table 2. Results of one sample t-test, mean values, mean differences, and SDs of power output values between CP and other performance indices (CP', RCP, EMGFT)

Variable	Mean	±SD	Mean difference	
			Mean	±SD
CP' (W)	95.11	8.99	44.31	8.99
RCP (W)	94.29	8.98	42.67	8.98
EMGFT (W)	95.62	8.49	–2.65	5.80

Note: CP' – critical power based on VO_2 kinetics, CP – critical power based on mathematical models, RCP – respiratory compensation point, EMGFT – EMG fatigue threshold, SD – standard deviation
Data are presented as means, SD and mean differences.

Discussion

This study was an attempt to investigate the fatigue threshold as a marker for transition from aerobic-to--anaerobic exercise intensity in intermittent sport players. Moreover, the authors also aimed to investigate the agreement between various fatigue thresholds (CP, CP', RCP and EMGFT). The crucial point emerging from this study was that CP based on mathematical models underestimates the boundary between heavy and severe exercise domain, in comparison to its physiologically evaluated substitute CP', which could be an answer to the query summarized in a review on critical power by Dotan [7].

Also, this is among the first few studies to directly demonstrate a commonality between these fatigue thresholds in intermittent sport players. Previous studies debated whether or not exercise conducted at or slightly over CP reached VO_{2peak} or not [8, 12]. The results of this study showed that VO_2 could be kept constant during exercises performed above CP (+15 W), but when CP' was exceeded by 15 W, the exercising VO_2 responses immediately increased and reached VO_{2peak} for each subject. Therefore, above CP', metabolic (phosphocreatine, pH) and systemic (VO_2, blood lactate) homeostasis decreased, validating the notion of a "critical metabolic rate" (above which intramuscular phosphocreatine, phosphate ions and pH could not be stabilized) [25, 26].

RCP and CP' were shown to be in accord with one another in our investigation, but not with CP, similarly to the result reported by Ozkaya et al. [21]. The reason behind these changes can be the rapid compensatory reflex increase in ventilation (i.e., RCP) brought on by intensities above the critical metabolic rate, which overwhelms this regulatory system, leading to a near--immediate accumulation of hydrogen ions, an uncoupling of ventilation from carbon dioxide (CO_2) production, and a systematic decrease in end-tidal partial pressure of CO_2. By evacuating CO_2 from the lungs at a speed comparable to its synthesis, the hydrogen ion concentration is related to both metabolic and non-metabolic CO_2 production [24]. Importantly, RCP must happen after the critical metabolic rate, hence in this instance CP' applies. Thus, CP' and RCP may be a superior approach to determine the lower boundary of the severe exercise domain [21]. In the heavy intensity domain, however, there are increases in EMG amplitude. Furthermore, the fatigue-induced increase in muscle activation suggests that the increase in EMG amplitude, which is used to determine EMGFT, is due primarily to increases in motor unit recruitment [5, 18]. Also, RCP and EMGFT corresponded to the similar work rates. Similar to our study, Zuniga et al. [28] and Bergstrom et al. [2] indicated that the work rate corresponding to EMGFT was equal to RCP based on the disassociation of VE from VCO_2. According to Darabi et al. [6] and Bergstrom et al. [2], "the disassociation of VE from VCO_2 may be more closely related to the stimulation of peripheral catecholamine by increased arterial potassium". Indeed, it was previously observed that the change in ventilation associated with RCP was produced by increases in the circulatory concentration of potassium released from the recruitment muscle fibers [17]. It can also be postulated that if the subject can reach an intensity of RCP, then EMGFT should occur, which is also supported by a study done by Mäestu et al. [17]. CP' was also in accord with EMGFT, which was a novel finding to this study, moreover, this can be a response to the increasing rate of hyperkalemia [21]. EMGFT reflects the recruitment of additional motor units, increased firing rates, and/or synchronization [1]. The result of this study supports the previous finding that EMGFT can be an alternative to open-circuit spirometry to detect an aerobic to anaerobic transition in athletes on a cycle ergometer [13]. Even if some scientists theorize that CP best depicts the upper limit boundary of heavy exercise domain exercise, the result of this study can support the findings of Ozkaya et al. [21] that there is a significant gap between heavy and severe exercise domains, which was referred to as the “grey zone”.

The limitation of this study was being a sex-biased study. Future studies can focus on evaluating these trends in female athletes. Moreover, in this study the sample was taken from the intermittent sports players only, therefore the results will only be applicable to these players, hence lacking generalizability to all the sports players. Future studies should analyse estimation of various fatigue thresholds in different populations.

Conclusions

Critical power can truly be estimated physiologically via VO_2 kinetics (CP’), rather than being mathematically derived (CP). Therefore, CP’ can help in evaluating performance efficiency and also helps monitor the effect of training programs especially for interval training protocols and team sports such as association football, rugby and hockey. As RCP and EMGFT agree with CP’, therefore CP’, RCP, and EMGFT can be considered as the boundary between aerobic and anaerobic work rates or heavy and severe exercise domains. CP’ can be used as a surrogate to EMGFT and RCP and vice versa, therefore, evaluating either one of them can give an overview of exercise tolerance and fatigue resistance of the intermittent sport players. CP’ should be evaluated individually of all athletes to have the best-fit prescription for the high or severe intensity exercise in athletes. However, if critical power is evaluated using mathematical models, then the possibility of the grey zone between heavy and severe domains should be considered during testing and training.

Conflict of Interest

The authors declare no conflict of interest.

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