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original article

Can neuromuscular fatigue threshold be determined by short and non-exhaustive bouts?

Pode o limiar de fadiga neuromuscular ser determinado por testes curtos e não exaustivos?

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Resumo – The present study determined the neuromuscular fatigue threshold (NFT) using four different time-periods of analysis of the electromyographic signal and compared these estimations with critical power (CP). Fifteen healthy young men (73.6 ± 5.1 kg, 177.8 ± 7.0 cm, 23.4 ± 5.2 years) performed 3-4 different severe constant workload trials until exhaustion on a cycle ergometer with simultaneous SEMG signals acquisition. The obtained data permitted NFT estimation with four different periods of analysis as follows: initial 30s (T30), 1min (T1), 2min (T2) and total time (TT), as well as CP. T30 and T1 were significantly higher than TT and CP and, T2 and TT did not differ between each other, and both were significantly higher than CP. In addition, TT was significantly correlated to CP (0.72; $P < 0.05$) and to T2 (0.58; $P < 0.05$). We conclude that NFT overestimates CP, independent of the time-period analysis used for its determination.

Palavras-chave: Electromyography; Exercise test; Muscle fatigue; Physical fitness.

Abstract – *O presente estudo determinou o Limiar de Fadiga Neuromuscular – LFNM usando quatro diferentes períodos de análise do sinal eletromiográfico e comparou essas estimativas com a Potência Crítica - PC. Quinze homens saudáveis do sexo masculino (73,6 ± 5,1 kg, 177,8 ± 7,0 cm, 23,4 ± 5,2 anos) realizaram 3-4 testes severos de carga constante até a exaustão em um cicloergômetro com simultânea aquisição de sinais SEMG. Os dados obtidos permitiram a estimativa de LFNM em quatro períodos diferentes: 30 segundos iniciais (T30), um minuto (T1), dois minutos (T2), tempo total (TT), assim como PC. T30 e T1 foram significativamente maiores do que TT e PC e, T2 e TT não se diferiram entre si e foram maiores que PC. Além disso, TT foi significativamente correlacionado com PC (0,72; P < 0,05) e com T2 (0,58; P < 0,05). Dessa forma, conclui-se que LFNM superestima PC, independente do tempo de análise utilizado para sua determinação.*

Key words: *Condicionamento físico; Eletromiografia; Fadiga muscular; Teste físico.*

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INTRODUCTION

Aerobic training has been widely used throughout several sports modalities and recreational physical activities. The role of the intensity has been shown to be determinant to produce positive effects on this type of exercise[1,2]. Usually, coaches and trainers apply testing protocols in order to identify aerobic parameters to use as reference markers on the day-by-day training sessions[3,4]. However, most of these tests involve expansive equipments and exhaustive procedures[4,5], which become unpractical for most of the athletes. Therefore, simple and practical methods that indicate training intensities might optimize training prescription and evaluation of exercise programs.

Surface electromyography (SEMG) has been demonstrated to be an interesting non-invasive method to quantify neuromuscular fatigue[6]. The technology improvement of the last two decades has turned this method attractive to clinicians and researchers, as well as coaches and physical trainers, since with simple procedures and good data quality, muscular endurance indices can be easily assessed[7,8]. deVries et al.[9] using SEMG analysis, suggested a procedure to determine the highest intensity sustainable without evidence of neuromuscular fatigue. The so-called neuromuscular fatigue threshold (NFT)[10], has been derived from a linear rate of increase of the exercising muscle electric activity (SEMG slope) during 3-4 constant high-intensity workloads (i.e., not until exhaustion). A linear regression between SEMG slope and intensity predicts the power output associated with zero SEMG slope, which theoretically corresponds to the upper limit of exercise without neuromuscular fatigue[10,11]. The NFT is highly related to performance[10] and can be used as a parameter for physical training or fitness evaluation[11]. However, controversial data is presented when comparing NFT with other well established aerobic indices[10-14]. Such a discrepancy could be attributed to the different periods of the SEMG signal analysis of the constant workload tests since one and two minutes, or total trial duration have been used.

The critical power (CP) has been shown to be a reliable and non-invasive aerobic index[15,16]. Contrary to NFT, CP has presented consistent results when assessing aerobic capacity[17,18]. In this procedure, only workloads and the respective times to exhaustion are used to fit the predictive equations[15]. Despite its consistency, CP requires the subjects to perform exhaustive predictive tests, which make difficult its application in some populations such as obese, elderly and children, as well as diseased population, due to the inherent discomforts associated with maximal efforts. Thus, valid and reliable protocols with lower metabolic disturbances seem to be interesting to predict aerobic indices for different individuals. Furthermore, the determination of the NFT by non-exhaustive and short work bouts would improve its practical application, in particular among special populations, avoiding strenuous exercise to be performed. In addition, high performance athletes may also be benefitted by this procedure by allowing constant examination of the performance and training intensities.

Hence, the purposes of the present study were (1) to establish the NFT calculated from different periods of analysis of the SEMG signal during the constant workload tests and (2) to compare these estimations with CP. We hypothesized that all periods of analysis would estimate similar values for NFT, and that they would not differ from CP.

METHODS

Subjects

Initially, 15 healthy young men (73.6 ± 5.1 kg, 177.8 ± 7.0 cm, 23.4 ± 5.2 years) volunteered to the present study, however, one dropped out after reporting extreme discomfort during the first test, and was excluded. The participants were physically active (~3 session per week of recreational physical activities) and non-smokers, and were also instructed to avoid vigorous activities and to not ingest beverages containing alcohol or caffeine in the 24-h prior to each test. All the subjects were fully informed about all testing procedures and completed a health questionnaire before signing a written informed consent. This study was approved by the local Ethics Committee. All procedures were performed according to the Declaration of Helsinki.

Experimental design

All the testing procedures took place within 4-week period. Each subject reported to the lab 5 times. The subjects were all fully familiarized with the tests and experimental procedures, since they had already participated in previous studies with similar design and equipments. The tests consisted of 3-4 different severe constant workload trials, performed randomly until exhaustion on a cycle ergometer, with simultaneous SEMG signals acquisition (as described in *SEMG recordings and analysis*). The obtained data permitted NFT estimation with four different periods of analysis as follows: 30s, 1min, 2min and total time; they also permitted CP to be calculated. These estimations were then compared and correlated to each other to test the hypothesis that they would not be different and would represent similar physiological indices (i.e., upper limit intensity maintained without neuromuscular fatigue).

Predictive tests

The subjects performed 3-4 exhaustive tests on separated days to estimate the NFT and CP. All the tests were performed on an electronically braked cycle ergometer (Corival-400, Quinton Instruments, Netherlands). Individual seat and handlebar heights were recorded in the first test and reproduced for all subsequent tests, in such a way that there was a slight bend in the knee joint when the pedal was at its lowest point. Subjects were required to keep an upright trunk position throughout the trials. Prior to each test, a warm-up at 50 W was carried out for 3-min, followed by 2-min rest. The power outputs during the tests were empirically chosen in order to induce exhaustion within 1-15 min, as previously described[11,14]. All tests were performed at approximately the same time of the day. The participants were instructed to maintain a fixed cadence of ~60 rpm and exhaustion was considered as the incapacity to sustain the cadence for ~5 s, despite strong verbal encouragement. The exhaustion time was recorded to the nearest second. No feedback about the power output or elapsed time was provided to the subjects during the trials. The SEMG signals were continuously recorded until exhaustion (as described below).

SEMG recordings and analysis

For SEMG recording, active bipolar (20 mm center-to-center) surface electrodes (TSD 150TM, Biopac Systems®, CA, USA; common mode rejection ratio, 95 dB) were used to record activity from the vastus lateralis muscle on the dominant side of the body. The electrodes were positioned between the motor point and the proximal tendon[19]. Inter-electrode impedance was minimized by careful skin shaving and alcohol cleaning. The reference electrode was placed over the anterior iliac crest. The SEMG signal was amplified (MP150 Electromyogram Amplifier, Biopac Systems Inc, Santa Barbara, Ca. USA) with a frequency band ranging from 20 to 500 Hz. SEMG signal was digitized with a sampling frequency of 2000 Hz and processed by calculating the *root-mean-square* (RMS) of 5 s periods (AcqKnowledge 3.8.1TM software, Biopac Systems®, CA, USA). All data were normalized as a percentage of the initial 5 s period from each constant load test.

Determination of Neuromuscular Fatigue Threshold (NFT)

The NFT was estimated by the mathematical model proposed by deVries et al.[9], in which the SEMG slope in function of time from each of 3-4 constant-load tests (Figure 1) is plotted against its respective power. The NFT is considered the *y*-intercept from the projected regression line (Figure 2), which, in theory, represents the maximal power that can be performed for long periods without evidence of neuromuscular fatigue. This procedure was completed to each time period of analysis: initial 30 seconds (T30), 1 minute (T1), 2 minutes (T2) and total time (TT).

1a

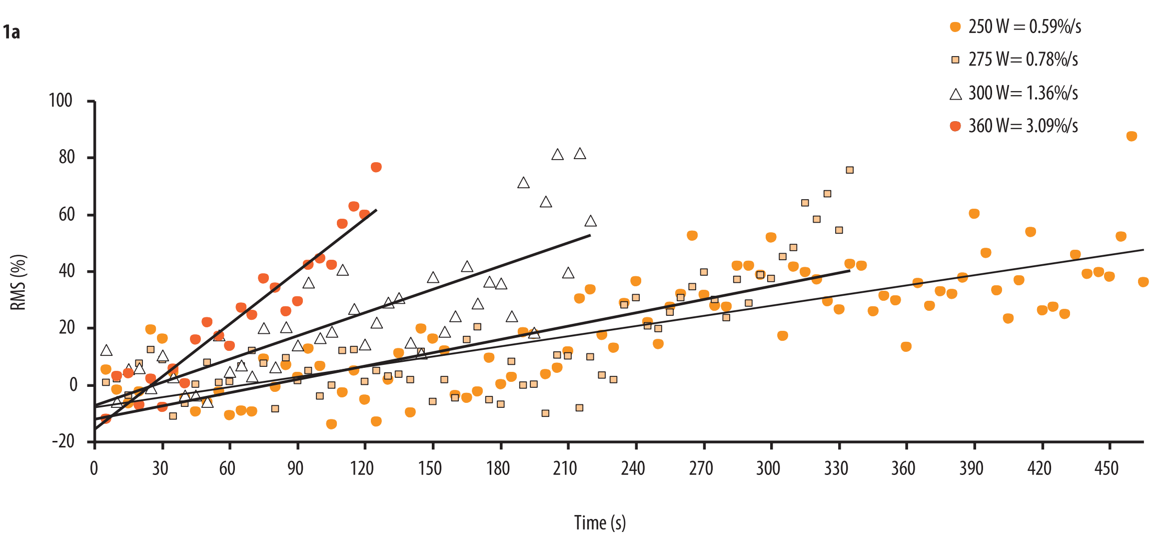

Figure 1a. Rate of SEMG increase (slope - %.s^{-1}) during four workloads performed by one subject.

1b

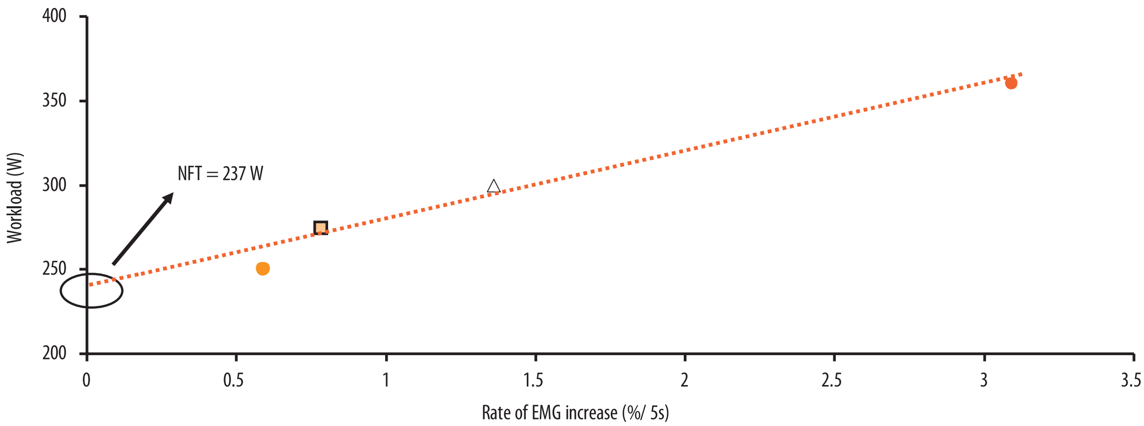

Figure 1b. Determination of the neuromuscular fatigue threshold (NFT) obtained via regression line between the rate of SEMG increase (slope - $\%.s^{-1}$) and respective power output.

Statistics

The results are presented as mean ± standard deviation. After normality assurance, ANOVA for repeated measures was used to compare NFT established by different periods of analysis and CP, while Scheffé *post hoc* test was applied to identify the differences when necessary. The correlation between variables was determined using Pearson product-moment correlations. The significance level was set at $P < 0.05$ (STATISTICA 6.0™, STATSOFT®, OK, USA).

RESULTS

The mean power outputs and times to exhaustion from the constant workload tests were 231, 264, 287 and 325 W, and 531, 289, 204 and 136 s, respectively. The SEMG slope ($\%.s^{-1}$) and their respective coefficient of determination (r^2) for all constant workloads in the different periods of analysis are presented in Table 1. Table 2 depicts the NFT estimations based on the different periods of analysis (T30, T1, T2 and TT), as well as the CP estimation. T30 and T1 were significantly higher than TT and CP. Despite the fact that T2 and TT did not show difference between each other, both were significantly higher than CP. In addition, TT was significantly correlated to CP (0.72; $P < 0.05$) and to T2 (0.58; $P < 0.05$).

Table 1. Rate of SEMG increase (slope - $\%.s^{-1}$) and its respective coefficient of determination (r^2) for all constant workloads (W) in the different periods of analysis (T30, T1, T2 and TT).

	T30		T1		T2		TT	
workload (W)	slope	r^2	slope	r^2	slope	r^2	slope	r^2
231	-0.24	0.05	0.13	0.36	0.04	0.02	0.18	0.4
264	1.11	0.92	0.84	0.29	0.26	0.21	0.33	0.62
287	1.3	0.75	1.04	0.25	0.12	0.21	0.47	0.71
325	4.37	0.31	3.62	0.43	0.18	0.56	0.59	0.74

Table 2. Neuromuscular fatigue threshold (NFT) values determined from different periods of analysis (T30, T1, T2 and TT) and critical power (CP), with their respective coefficient of determination (r^2). Values are presented as means ± SD.

	T30	T1	T2	TT	CP
NFT (W)	266,9 ^{abc*} ± 26.0	243,4 ^{a} ± 16.2	232.6* ± 18.3	217.2* ± 23.1	177.9 ± 27.3
r^2	0.47	0.65	0.8	0.95	0.93

^{a} *P* < 0.01 vs. TT; ^{b} *P* < 0.01 vs. T2; ^{c} *P* < 0.01 vs. T1; * *P* < 0.01 vs. PC.

DISCUSSION

The main findings of the present study indicate that the increase of the SEMG during high intensity and constant workload is not linear and, NFT varies when estimated from different periods of SEMG analysis (30s, 1min, 2min and total time). In addition, all the NFT estimations were significantly higher than CP.

The increase in the amplitude of the SEMG during constant workload exercise has been suggested to be associated to the additional and progressive recruitment of larger motor units to maintain the force-loss from the fatigued fibers[11]. According to the Henneman size principle, these larger motor units would innervate larger muscle fibers and consequently generate higher amplitude of the SEMG signal when activated. In addition, the intramuscular accumulation of hydrogen ions (H+) and decrease in pH during high-intensity exercise has been shown to impair muscle contractility, making it necessary to recruit additional motor units to maintain the required metabolic rate[11,20]. Thus, we believe that the exhaustive workloads performed in the present study might had induced similar physiological changes mentioned above. Moreover, the higher rates of SEMG activity found during the higher workloads may also be explained by the similar mechanism since greater physiological disturbances are evidenced in such intensities.

deVries et al.[9] using exhaustive, but short time periods bouts (1~4min), originally proposed NFT as a method to evaluate the aerobic capacity which, in theory, represents the highest intensity with steady state of muscle recruitment. However, these authors observed that the NFT overestimated CP in 11%, but both were highly correlated (r = 0.86). Our results confirm this overestimation, as well as the correlation between the NFT and CP during the TT analysis (22% and r = 0.72, respectively). Therefore, the intensity predicted by the NFT seems to not represent the same phenomenon that CP (i.e., highest intensity that can be performed by long periods without exhaustion[15]). Additionally, Pavlat et al.[12] verified the time to exhaustion during constant load cycling exercise at the power output corresponding to the NFT, and showed that subjects were able to sustain the exercise for only 225 ± 72 s. However, the authors limited the analysis to the first minute of the SEMG signal which, according to our findings, results in a greater power output estimation when compared to 2 min and total time NFT estimations. More recently, Kandell et al.[21] indicated that NFT were able to detect improvements of aerobic capacity after three weeks of high intensity interval training, but it did not change after 6 weeks when even though ventilatory threshold increased. We believe that this may be attributed to the improvements in discharge rates of motor units[22] (e.g., additional recruitment of motor units during constant load) which may be more evident during initial phase of fitness programs. Furthermore, Mäestu et al.[10] showed that NFT established in rowers overestimated the ventilatory threshold, however, when using total time-period, NFT showed a high relationship to performance (r=0.96). Together, the data provided by Kandell et al.[21] and Maestu et al.[10] may suggest that, despite this method does not represent the transition of aerobic / anaerobic metabolisms, NFT may be associated to the accumulation of muscle fatigue and able to detect neural adaptation to training.

Several studies have been using SEMG to estimate the aerobic-anaerobic transition during incremental exercise[23-25], the so called electromyographic threshold. However, this protocol is high metabolic demanding and its practical application is limited on the day-by-day fitness programs. On the other hand, Nakamura et al.[26] have provided a new method to estimate critical power by non-exhaustive tests using the ratings of perceived exertion. But, despite the fact that this method showed to be a reliable aerobic index for whole body capacity, limited information is available for local and specific muscle adaptation. Therefore, the present study aimed to verify if NFT from a representative exerting muscle in cycling (i.e., VL) could be enhanced by enabling its determination with very short and non-exhaustive exercise. We determined NFT with 30s of SEMG data from each workload performed, and unfortunately, our data showed that both NFT estimated by T30 and T1 were significantly higher than T2 and TT. This overestimation by lower periods of SEMG analysis may be explained by the fact that the SEMG signals, when treated in RMS and plotted against time, do not present a linear fashion throughout the high intensity and constant workload tests, even though several studies showed its linearity[9-11,21]. Hence, our data indicated that this aspect may vary according to the time period used for the analysis. Additionally, we observed that the highest coefficient of determination was found during the TT analysis (Table 1), meaning that the most linear pattern and, consequently, the most useful information of neuromuscular fatigue arises from this analysis. This dissociation of linearity behavior during the exercise may be explained by (1) the activation of different muscle fiber types along the exercise, which can result in different SEMG activity[24,25]; (2) the muscle activation pattern among the muscles' limb may change to maintain the constant workload during fatiguing cycling[27]; and (3) the time window for the RMS averages used here was 5s, and not the usually 10s used[9-11,21], which might be more sensitive to small changes in cadence during the tests and consequently induce higher variation in SEMG plots. Furthermore, we believe that less smoothed data in this case might indicate more reliable information of muscle activity during fatiguing exercise, in particular during shorter period, as the 30s used in this study.

In addition, our data showed that there is a tendency for the longer periods of analysis to estimate lower NFT values (Table 2). This latter observation implies that the SEMG slope is low in the beginning of the tests and increases towards the end. In this way, Smirmaul et al.[28] identified a break-point in different lower limb muscles (i.e., Vastus Lateralis; Rectus Femoris; Biceps Femoris; Semitendinosus; Tibialis Anterior) during constant workload cycling. We believe that the initial muscle activity should be more related to oxidative muscle fibers which have been suggested to be less fatigable than the glycolytic fibers. Thus, when the oxidative fibers were not able to sustain the required workload, the non-oxidative may play a more significant role on maintaining required exertion and higher rates of additional muscle recruitment might be observed. Furthermore, our results are in agreement with the data provided by Camata et al.[29], which also showed higher rates of muscle recruitment during the later periods of similar exhaustive exercise.

CONCLUSION

In light of the results, it is possible to conclude that NFT can not be used interchangeably with CP, since the former overestimated the latter in 22%. In addition, the NFT estimation using different time of SEMG analysis produces different results when compared to each other, suggesting that the rate of increase in the SEMG signal is not constant throughout the constant load tests. We suggest that the NFT is not a reliable method to evaluate the aerobic capacity during whole body exercises. Further investigation should aim to present a method to estimate aerobic capacity by non-exhaustive exercise that will be applicable in special populations, as obese and diseased, as well for high performance athletes during their training routine.

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