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Detection of the Anaerobic Threshold by Surface Electromyography

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***Abstract*— This work aims at presenting a method for automatic detection of the anaerobic thresholds by surface electromyography (*RMS-slope*) and compare with respective values identified by the analysis of ventilatory gas exchange. Thirteen healthy adults were submitted to a single maximal oxygen uptake test, being monitored the ventilatory parameters V_{O_2}, V_{CO_2}, and V_E, and the surface EMG (SEMG) of the right vastus lateralis muscle. Each cycle of myoelectric activity was automatically detected and the time series of the mean RMS values of these cycles used for determining the SEMG threshold (SEMG-T) by linear regression. The method was successful to determine SEMG-T for all subjects, with consistent results when compared to respective anaerobic thresholds visually estimated in the ventilatory equivalent V_E / V_{O_2}.**

***Keywords*— Surface EMG, Anaerobic Threshold, Exercise Physiology, Electromyography Threshold.**

I. Introduction

Early in Exercise Physiology, the subject performance in aerobic conditions was estimated by maximum capacity of the oxygen consumption ($V_{O_{2,MAX}}$) [1]. However, Heck *et al*. [1] showed that the aerobic performance can increase even when there is no significant increase of the $V_{O_{2,MAX}}$. Since then, the anaerobic threshold (AT) has been considered the main estimator of the aerobic performance. The AT can be defined as the exercise intensity in which the aerobic and lactic anaerobic metabolisms have the same contribution for ATP production [2]. Thus, for exercise intensities above AT the predominant metabolism is the lactic anaerobic and blood lactate accumulation will occur [3].

In spite of the historical controversy related to the physiological foundations of the AT existence [4-5], several studies were carried out to investigate different methods for AT identification. Initially, blood lactate measurements were used to identify the exercise intensity above which the lactatemia begins to present a significant increase [3]. Other authors assumed a constant value equal to 4 $mmol.l^{-1}$ for lactatemia at AT [1]. Among all the methods, the one widely adopted was the ventilatory threshold proposed by Wasserman and McIlroy [2], which is determined by a noninvasive technique. The theoretical foundation is that, during exercises with increasing intensity there is an approximately linear increase of the minute ventilation (V_E) and CO_2 production (V_{CO_2}), until the intensity named AT over which V_E and V_{CO_2} show nonlinearities [6]. These nonlinearities would be caused by a major buffering of the metabolic acids generated by the exercise, which indicates the anaerobic predominance [6]. Continuing the load increments, it can be observed a second nonlinearity at the V_E curve, which was labeled respiratory compensation (RC) [6]. Along the time, different automatic methods for detecting V_E and V_{CO_2} inflections were proposed, most of them based on linear regression [7].

Other noninvasive procedures used to estimate the AT were based on monitoring the superficial electromyogram (SEMG) by means of amplitude and frequency parameters [8]-[10]. This approach has the advantage of allowing the detection of anaerobic threshold without the use of any equipment for gas exchange measurements, when the protocol already requires the SEMG recording. Additionally, this approach may be considered for tests involving exercises of specific and limited group of muscles (e.g. localized fatigue), which is not expected to cause systemic metabolic changes. However, some of the studies that presented high correlation and equivalence between AT and SEMG threshold (SEMG-T), showed limitations related to signal acquisition and processing [8]-[10]. In these works, some subjects were excluded of the test before comparison due to identification problems on AT or SEMG-T.

The aim of this work was to implement an algorithm for automatic detection of the AT by electromyography (*RMS-slope*) and compare resulting values with the AT identified by ventilatory gas exchange method.

II. Material and Methods

Thirteen healthy male subjects with age 21-32 years were selected to take part in the study, with body mass 73.9 ± 12.3 kg (mean ± standard deviation) and height 1.75 ± 0.1 m. The experimental protocol was previously approved by local ethics committee and all subjects signed a written informed consent. All subjects were practicing regular physical activity at the time of data acquisition.

The instrumentation consisted by a mechanically braked cycle ergometer (Monark, Varberg, Sweden), an analyzer of respiratory gas exchange VO2000 (Medgraphics, Minnesota, USA), an electromyograph (Biovision, Wehrheim, Germany) and an automated blood lactate analyzer Accusport (Roche, Basel, Sweden).

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Each subject was oriented to complete a single maximal oxygen uptake test with cadence 50 rpm, starting at a power output of 12.5 W, with 12.5 W/min work increments. The software Aerograph (Medgraphics, Minnesota, USA) computed the respiratory gas exchange parameters V_{O_2}, V_{CO_2}, and V_E in real time, allowing the visual inspection. SEMG were recorded from the right vastus lateralis muscle with Ag/AgCl electrodes (spherical, 10 mm diameter) Kendall MEDI-TRACE 2000 (The Ludlow, Chicopee, USA), and passed by a differential amplifier (gain 2500), with 120 dB common mode rejection, 1 TΩ input impedance and band limited between 10 and 1 kHz. After amplification, SEMG signal was filtered by a first order anti-aliasing Butterworth filter with 500 Hz cutoff frequency. The electrodes were fixed at two thirds on the line from the anterior spina iliaca superior to the lateral side of the patella. Electrodes were placed following the vastus lateralis fibers direction with 35 mm inter-electrodes distance, with the reference electrode placed on the right lateral malleolus. The skin was prepared by shaving the hair, abrasion with sponge and alcohol cleansing.

The respiratory gas exchange parameters were measured breath by breath and averaged on each three cycles. SEMG was digitized at 2 kHz through a data acquisition board DacCard 6024E (National Instruments, Austin, USA), with 12 bits resolution, dynamic range of ±5 V, and the data acquisition software was built using Labview 5.0 (National Instruments, Austin, USA). The lactatemia was measured immediately after test.

The AT was identified by visual inspection (a single expert) in the ventilatory equivalent of oxygen (V_E/V_{O_2}) curve. The threshold corresponded to the point after which this signal exhibited a systematic increase without a concomitant increase in the ventilatory equivalent of carbon dioxide (V_E/V_{CO_2}) curve.

SEMG was pre-processed by a digital filter whose coefficients were obtained by the convolution of eight filters (Fig. 1): high-pass 2nd order Butterworth, cutoff frequency 10 Hz; low-pass 8th order Butterworth, cutoff frequency 400 Hz; and six 2nd order notch filters to attenuate 60 Hz mains noise and its harmonics until 360 Hz (Fig. 2). SEMG was filtered in direct and reverse directions to avoid phase shifts and thus decimated to 1 ksamples/s.

For the identification of the segments of myoelectric activity in the SEMG, it was implemented an algorithm that firstly detects data segments with a fixed threshold [11], which corresponds to the sextuple of the baseline noise standard deviation. The onsets and ends of the myoelectric activity epochs are identified when the root mean square value (RMS, 20 ms window) crosses the threshold upward and downward, respectively (Fig. 3).

The time series of the mean RMS (mRMS) from each myoelectric activity epoch was analyzed by the algorithm *RMS-slope*, similar to the one usually adopted for *v-slope* [7]. The time series was smoothed by a moving average filter (25 samples) in direct and reverse directions to avoid phase shifts. Two regression lines were thus fitted to the initial and terminal portions of this time series, with the sum squared error (SSE) being stored during iterative changes of the intercept between these straight lines. The inflexion point given by the intercept that corresponds to the minimum SSE was assumed as SEMG-T if the change in slope between lines was greater than 15%.

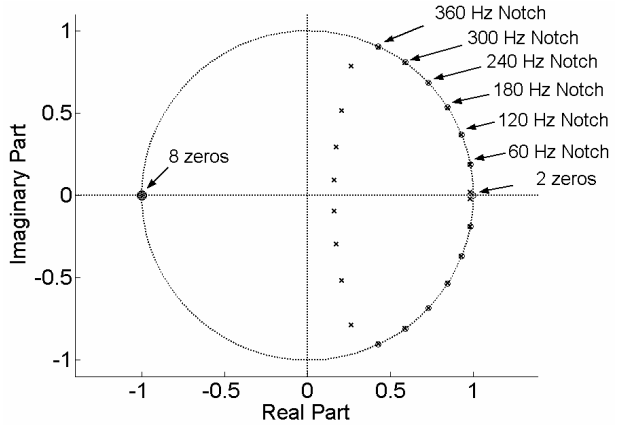

Fig. 1. Poles and zeros diagram of the digital filter in z-plane.

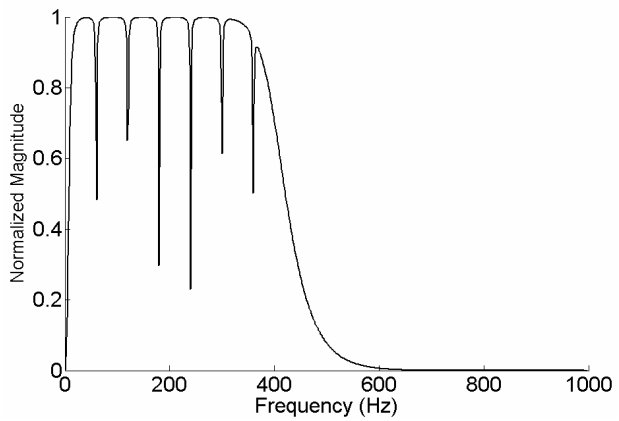

Fig. 2. Frequency response of the digital filter.

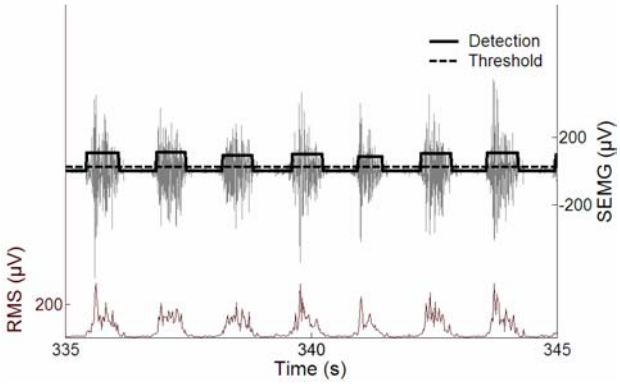

Fig. 3. Detection of SEMG activity epochs during the cycle ergometer test.

Both AT and SEMG-T values were expressed in power output (W) and compared using Bland-Altman plot [12] and Wilcoxon test ($\alpha = 0.05$).

III. Results

The average lactatemia just after the test was 6.8 ± 1.8 mmol.l^{-1}, with $VO_{2,MAX}$ 39.8 ± 13.8 ml.kg^{-1}.min^{-1} and the respective power output 168.2 ± 31.7 W (Table I).

The *RMS-slope* algorithm successfully identified the SEMG-T for all subjects, at mean power output 146.2 ± 24.7 W. No significant difference was observed between SEMG-T and AT ($p = 0.1769$). This found is confirmed by Bland-Altman plot (Fig. 4), which shows no cases exceeding the two standard deviation limits for differences [12].

Fig. 5 and 6 show examples of SEMG-T and AT detection for one subject.

TABLE I
INDIVIDUAL AND MEAN VALUES OF METABOLIC PARAMETERS

Subject	Lactatemia (mmol.l^{-1})	$VO_{2,MAX}$ (ml.kg^{-1}.min^{-1})	$VO_{2,MAX}$ (W)	AT (W)	SEMG-T (W)
S1	7.8	38.1	150.0	87.5	137.5
S2	10.1	51.2	250.0	162.5	112.5
S3	8.0	53.8	175.0	150.0	112.5
S4	4.7	58.9	162.0	150.0	175.0
S5	7.3	34.3	175.0	162.5	175.0
S6	6.3	21.3	187.5	137.5	162.5
S7	6.7	52.3	162.5	112.5	162.5
S8	8.6	28.7	150.0	100.0	150.0
S9	4.6	36.1	125.0	125.0	125.0
S10	6.6	60.9	200.0	125.0	187.5
S11	4.3	24.9	150.0	125.0	137.5
S12	5.0	30.3	162.5	150.0	125.0
S13	8.0	26.7	137.5	125.0	137.5
Mean	6.8	39.8	168.2	131.7	146.2
SD	1.8	13.8	31.7	23.2	24.7

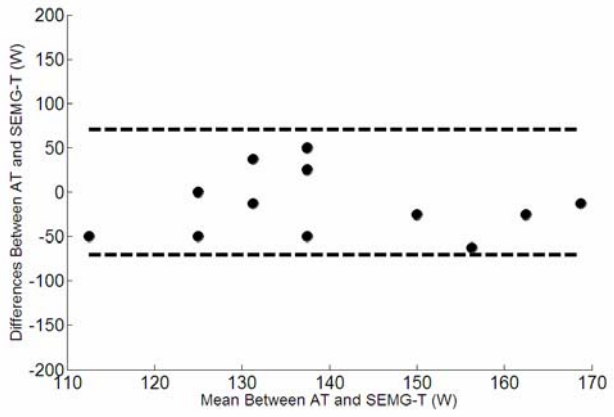

Fig. 4. Bland-Altman plot for the differences between AT and SEMG-T. Significant differences are expected to overcome the two standard deviation limits (dashed lines) [12].

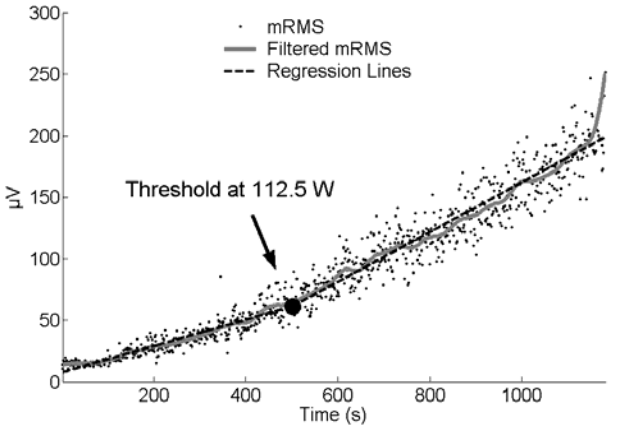

Fig. 5. Detection of SEMG-T using *RMS-slope* method (Data from subject S2).

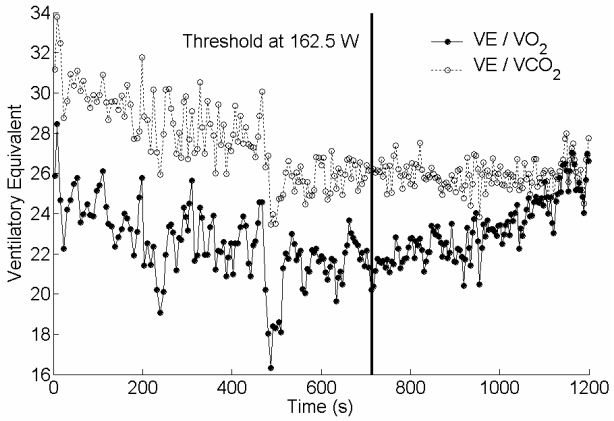

Fig. 6. Detection of ventilatory thresholds by visual inspection of the ventilatory equivalent. Vertical line represents the anaerobic threshold visually identified (Subject S2).

IV. Discussion

The lactatemia after test was greater than 4 mmol.l^{-1} for all subjects, confirming the transition from aerobic to anaerobic metabolism [1],[9].

By visual inspection of the Fig. 4, it can be clearly observed the point of inflection in the mRMS time series. This same pattern was observed for all subjects. Therefore, the *RMS-slope* method proved to be reliable, even by subjective analysis. However, other authors [10] mention that just 11 among 39 individuals showed nonlinear increase of the RMS value and this was attributed to the different muscular recruitment patterns among subjects. The current results do not confirm this hypothesis and suggest that observed divergences can be explained by differences in signal processing. In this sense, Hug *et al.* [10] do not informed if there was performed a previous detection of the EMG intervals corresponding to muscle activation, neither the size of the EMG epoch used for obtaining the RMS data, although these details may commit the SEMG-T detection.

Furthermore, these authors used the successive equal sized data epochs for estimating the power spectrum by Welch periodogram and obtaining median frequency and low and high frequency energy estimators. In such approach the greater problem is the non-stationarity of the SEMG in dynamic contractions, as pointed by [13]. Additionally, the current work has as advantage the increased time resolution given by one RMS value for each myoelectric activity, since Hug *et al.* [10] used only one RMS value (the last 20 s mean) for each power output step.

The present approach is similar to the one of Lucía *et al.* [8], who also detected AT by visual inspection but used a linear regression to find the inflexion point in the time series of SEMG integral (iEMG) calculated at each 2 s. Although these authors have identified SEMG-T for all subjects, it was based on fixed time scale along SEMG, which is not recommended as pointed before. The choice of the SEMG data segment is a possible cause of the discrepancies in SEMG-T values obtained by Taylor *et al*. [9]. Using 1 min epochs of the quadriceps muscles iEMG, these authors observed that only the rectus femoris muscle presented an exponential behavior and nonlinearity in the lactate threshold [9]. These founds suggest that the use of a fixed time window for extracting the SEMG parameter may be influenced by the varying amount of myoelectric activity in each window, which reinforces the proposed method of detecting each cycle of muscle activity.

The automatic AT detection using the ventilatory gas exchange parameters requires a robust method due to the initial behavior of the functions $V_E(V_{O_2})$ and $V_{CO_2}(V_{O_2})$. At the beginning of test these functions can have negative trends due to an anticipatory increase of the V_E controlled by brain cortex [14]. Thus, the *v-slope* algorithm efficiency depends on the selection of the onset of the signal for the regression analysis, mainly when AT identification is performed in tests without warm up [7].

As a conclusion, the proposed *RMS-slope* method based on the average of each muscular activity period during a single maximal oxygen uptake test with cycle ergometer allowed detecting SEMG-T values for all subjects, which are consistent with the anaerobic threshold, becoming an alternative to methods based on ventilatory gas exchange analysis.

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