



Temporal behavior of motor units action potential velocity under muscle fatigue conditions

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ABSTRACT

Muscle fatigue, which is defined as the failure to maintain a required or expected force, has been investigated in both clinical and sports applications. On the investigation of muscle fatigue effects related to muscular control, surface electromyography (SEMG) has been the most common electrodiagnostic method, because some different parameters can be extracted from the EMG signal. Among the parameters, motor units action potential conduction velocity (MUAPCV) has been one of the most important, in spite of being usually detected through indwelling electrodes. Thus, the aim of this work was to estimate MUAPCV through SEMG, detecting its temporal behavior during isometric contractions until exhaustion. Eighteen students from EEFD/UFRJ (9 men and 9 women – mean age 25.6 ± 6.8 years), right handed, consented to participate on this study. The EMG signals were collected from the right biceps braquii muscle through surface electrodes on 3 different levels of isometric contractions (25%, 50 e 75% of maximum load (ML)), which were divided into 3 periods that would define the beginning (P1), the middle (P2), and the end (P3) of the contraction. MUAPCV presented a temporal reduction with fatigue installation, showing a statistical difference among periods ($p < 0.0001$), comparing all the 3 loads. However, it was observed an abrupt decrease of MUAPCV at P3, mainly for 50 and 75% of ML. The results point out that MUAPCV must be quite sensible to pH reduction and changes on ionic concentrations, defined by blood supply decreases. Furthermore, the adaptations introduced on SEMG to MUAPCV estimation were considered satisfactory, reinforcing this method on electrodiagnostic evaluations.

INTRODUCTION

Muscle fatigue, which is defined as the failure to maintain a required or expected force⁽¹⁻³⁾, has been investigated in both clinical and sports applications. To understand the mechanisms involving the muscle contraction and regulation under fatigue conditions is very important as it is unchained by a series of factors such as the type of muscle involved, contraction duration, overload level and type of task performed^(3,4).

In the investigation of the fatigue effects on the control standards of the muscle contraction, the electromyography (EMG) has been the most employed electrodiagnostic technique and among the information extracted from the myoelectric signal, the amplitude temporal behavior is obtained by its average square root (RMS value) and in the frequency domain, the average frequencies (AF) and median (MF) are obtained with emphasis for the second one in function of its statistic characteristics⁽⁵⁾. Besides these variables, the muscular fibres action potential propagation velocity (MFAPCV) has also allowed the performance of several observations with regard to changes on the sarcolemma permeability in function of

Key words: Electromyography. Muscle fatigue. Motor unit action potential velocity.

the metabolites accumulation and consequently on its properties in relation to the MUAP propagation^(2,6).

In the investigation of the MFAPCV behavior, needle electrodes are introduced into the muscle, an invasive methods that brings higher precision to the monitoring of alteration as result of the fatigue process⁽⁷⁻¹⁰⁾. However, despite the fact that the invasive method brings higher methodological quality to procedure and higher reliability of information collected, needle electrodes also bring higher discomfort to patients or athletes when applied, higher costs and the requirement of tests of higher complexity. With the objective of solving such problems, different proposals are presented in literature for the estimation of the motor units action potential conduction velocity (MUAPCV) through surface electromyography (SEMG), where surface electrodes adapted for such purpose are used^(6,11,12). However, it is suggested that these electrodes, defined from a large number of small bars composed of silver and which dimensions may reach 1 mm of thickness and 5 mm of length, be series-configured and incrustated in plates specially constructed for this task⁽⁵⁾.

The main justification with regard to the use of this special type of electrode is defined by a lower noise receiving and a better EMG signal spatial resolution^(5,11).

So, the use of regularly commercialized electrodes constructed and adapted for this type of measure is required, what, still, presents high cost, impairing the access to the use of this technique.

Despite the non-invasive feature, the SEMG requires a higher computational processing for the estimation of the MFAPCV, once the electrodes will be receiving the algebraic sum of the muscle fibres action potential, thus representing the EMG raw signal⁽¹³⁾. Still, it has been demonstrated through the utilization of electrodes configured for this purpose as previously discussed, the effectiveness on the MUAPCV estimation through SEMG in different application conditions, except for those that demand dynamic contractions⁽¹¹⁾.

In this context, the objective of this work was to estimate the motor units action potential conduction velocity (MUAPCV), determining its temporal behavior under different muscle contraction levels until fatigue by means of the application of this technique, in other words, through simple adhesive surface electrodes.

MATERIAL AND METHODS

Eighteen students from the EEFD/UFRJ graduation course volunteered for the composition of the sample, being nine males and nine females (25.6 ± 6.8 years of age), right handed with no lesion history of the upper limbs muscle-skeletal system. All volunteers received orientation about procedures to be adopted and signed a consent form to participate in this study (project registered under number 125/03), approved and submitted to the Ethics Committee – HUCFF/UFRJ.

The acquisition system was composed of a computer (Pentium – 200 MHz), an analogical-digital converter (DaqPad 1200 – NA-

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TIONAL INSTRUMENTS, USA) with 12 bits and dynamic range of ± 5 V. For signals receiving, a system with cables with amplifier developed in the EEFD/UFRJ Biomechanics Laboratory was used, with frequency range limited between 10 and 500 Hz and total gain of 1000, according to norms of the European Recommendations for Surface Electromyography⁽⁶⁾. The signals acquisition and processing programs as well as the programs developed for the performance of power tests were elaborated in LabVIEW (NATIONAL INSTRUMENTS, USA). Ag-AgCl surface electrodes (Meditrace® 200 – KENDALL, Canada) were used for the acquisition of the EMG signals. The sampling frequency adopted was 2 kHz.

For the performance of the fatigue tests, a mechanical device for the support of the right upper limb was developed and a dynamometry system with individual adjustment of height and distance in relation to the right shoulder articulation was used (figure 1). During the performance of the tests, each volunteer remained sitting with hip and knee articulation inflected at approximately 90° and the upper limb positioned according to figure 1.

The experimental protocol was composed of a maximal load test (ML) with duration of 5 s that preceded the signals collecting stage. The percentile loads employed during the fatigue tests were calculated from the maximal load reached as follows: 25%, 50% and 75% of the ML. The tests were performed in 3 different days with minimal interval of 48 h. Each test consisted of isometric contractions maintained until exhaustion by means of visual feedback with the aid of a computer monitor (figure 1) for each load employed in random order. The computer monitor remained at a distance of approximately 75 cm from the volunteer, being only adjusted vertically.

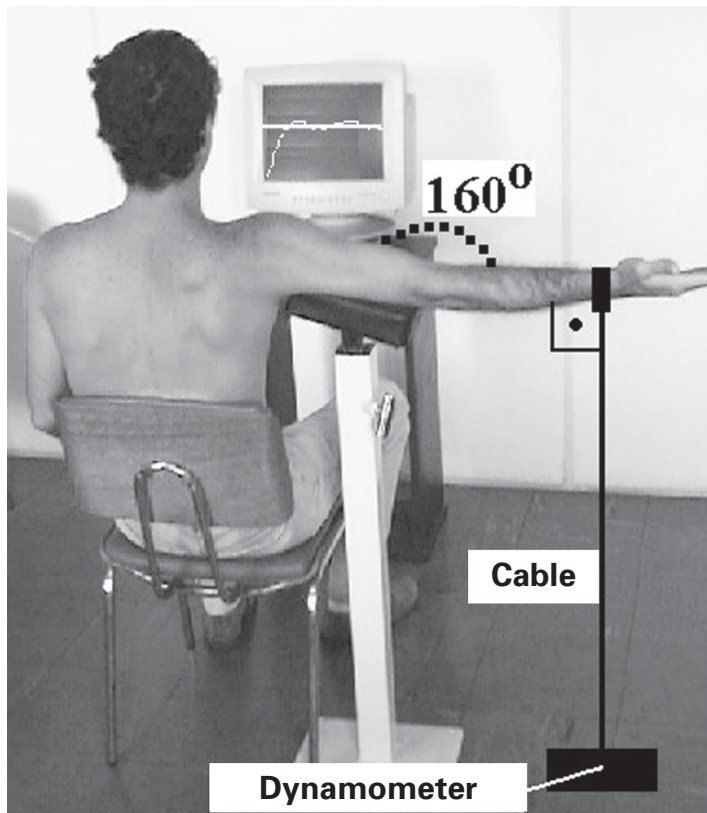


Fig. 1 – Position adopted by subjects during the EMG signal collecting stage. The target load mark and the force level tracing are given in the computer monitor.

The acquisition of the power signals and EMG was defined from the beginning of the contraction and interrupted when the force could no longer be maintained in approximately 30% of the pre-established load.

Before the application of the electrodes, the area was trichotomized with razor blade and cleaned with neutral soap. The electrodes were applied on the ventral region of the right biceps braquii muscle, according to protocol suggested by Hermens *et al.*⁽⁶⁾. However, for the calculation of MUAPCV, the protocol was modified for the application of a third electrode. The distance between the acromium and the cubital tunnel was measured and the first electrode applied at 1/3 from this last one. The other two electrodes were applied on the line projection between the anatomical points used as reference (figure 2). The reference electrode was applied on the humerus medial epicondylis.

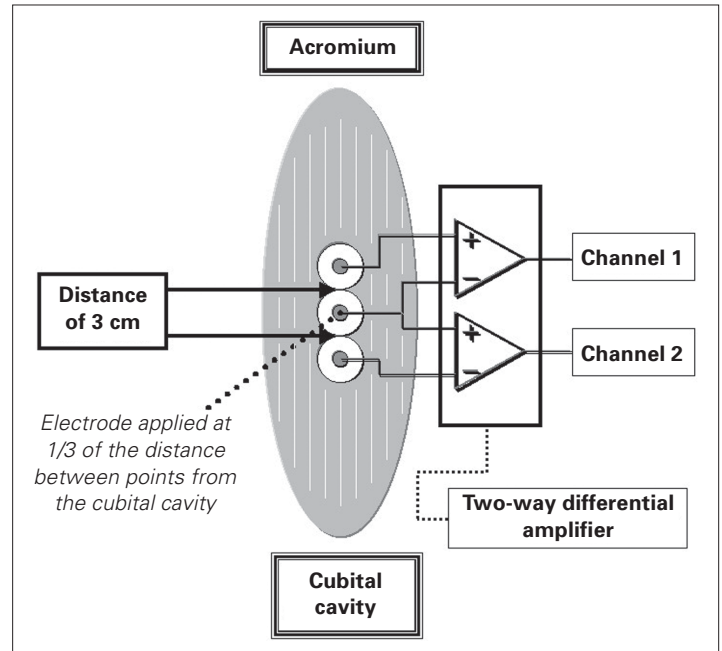


Fig. 2 – Simplified scheme of the surface electrodes disposition on the ventral region of the right biceps braquii muscle.

For the estimation of the MUAPCV through surface electrodes, the method suggested by Nishizono *et al.*⁽¹¹⁾ was used. From the crossed correlation test between both signals received (channels 1 and 2), obtained from windows of length L , arbitrarily defined as equal to 2000 samples and equivalent to 1 second of signal and identifying the crossed correlation vector element index that present the maximal value of IC_{max} , it is possible to calculate MUAPCV through equation 1.

$$MUAPCV = \frac{D}{(IC_{max} - W)} \times SR \quad (1)$$

Where,

D is the distance between the electrodes, equal to 3 cm;
 SR is the sampling rate, equal to 2000 samples/s;
 W is the window of 2000 samples.

For a better understanding of the procedure adopted, the estimation of MUAPCV is presented below (figure 3) through simulated signals and window W of size equal to 500 samples.

As previously discussed, the MUAPCV was calculated from each second of signal, resulting in a data temporal series which sizes present differences between subjects. These differences occurred in function of times spent with the maintenance of the contraction in each situation tested until exhaustion. Therefore, for statistical treatment effects and results presentation, it was arbitrarily opted to subdivide each valid temporal series into 3 different equidistant periods with duration of 5 seconds each. The valid temporal series was defined as all signal period referent to the maintenance of the

contraction, in other words, to the maintenance of the force up to 15% below the target load (figure 4). Thus, each test resulted in 3 periods that best represented the initial (P1), intermediate (P2) and final (P3) behaviors of all experiment (figure 4). For the selection of the periods, the following method was adopted: P1 was defined as the 5 initial seconds; P2 defined as the 2 seconds anterior and posterior to the median, also included, from the valid period of the temporal series and P3 defined as the 5 final seconds. Later, the average of each period was calculated and only three reference values of the MUAPCV were verified for each subject for each one of the loads analyzed. In the analysis of data, comparisons between periods (initial (P1), intermediate (P2) and final (P3)) and between loads (25%, 50% and 75% of the ML) were performed through the application of the two-way ANOVA for repeated measures and Tukey's *post-hoc* test with significant level (α) equal to 0.05. The analysis of data was performed through the statistical package STATISTICA® 6.0 (StatSoft, USA).

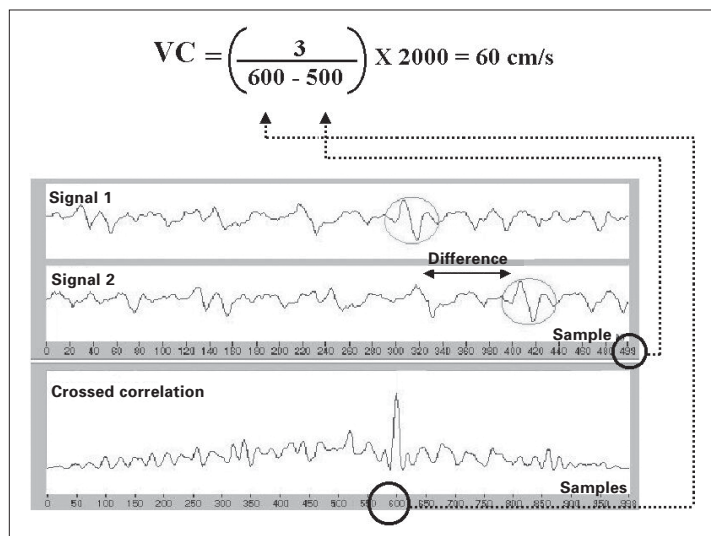


Fig. 3 – The difference presented by signals 1 and 2 collected by the pairs of electrodes and of sizes equal to 500 samples (L) is of approximately 100 samples. As the sum of both windows totalizes 1000 samples and the difference is equal to 100, the highest correlation value approximates of the sample of number 600, thus being possible to estimate MUAPCV through the equation 1. The distance between electrodes, adopted for the calculation was of 3 cm and the sampling frequency of 2000 Hz.

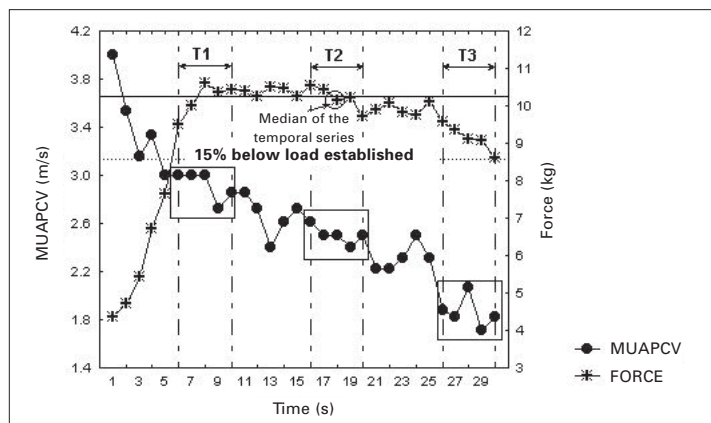


Fig. 4 – Example of temporal behavior of variables MUAPCV (m/s) and force (kg) of one of the subjects from the sample in periods selected (P1, P2 and P3) from the median during the maintenance of a contraction at 75% of the ML. The periods emphasized of the MUAPCV represent those periods extracted for the statistical analysis. It is observed that the periods were extracted from the signal collected from the force maintained up to 15% below ML (broken line).

RESULTS

Table 1 presents the average times spent in each load applied in the fatigue tests, reflecting the effort intensity.

Percentile loads	25% of the ML	50% of the ML	75% of the ML
CMT (average \pm SD)	213 s (\pm 113 s)	91 s (\pm 55 s)	56 s (\pm 33 s)

ML = Maximal load; CMT = contraction maintenance time.

When we compare periods P1, P2 and P3 between the different CVM percentile levels, no significant difference was observed for factor "load" ($F_{(2,51)} = 0.804$; $p = 0.45$), but observed between periods ($F_{(2,102)} = 34.36$; $p < 0.0001$) as well as a significant interaction between these two factors ($F_{(4,102)} = 2.63$; $p = 0.03$). The Tukey's *post-hoc* analysis showed that when the period P3 was compared between loads, a significant difference between 25% and 50% ($p = 0.04$) and 25% and 75% ($p = 0.01$) of the ML was observed, resulting in significant drop of the MUAPCV at the final phases in these loads. This kind of behavior is corroborated by some results found in literature^(3,12,15). Some of these works support the idea that the drop rate of the MUAPCV is determined by the load level (LL) applied and by the contraction maintenance time (CMT) (table 1); important variables in control conditions of the muscle fiber membrane permeability that will influence the propagation of the action potentials^(3,16), as already discussed. On the other hand, when loads of 50% and 75% of the ML were compared in this same period (P3), no significant difference was observed ($p > 0.05$) (figure 5).

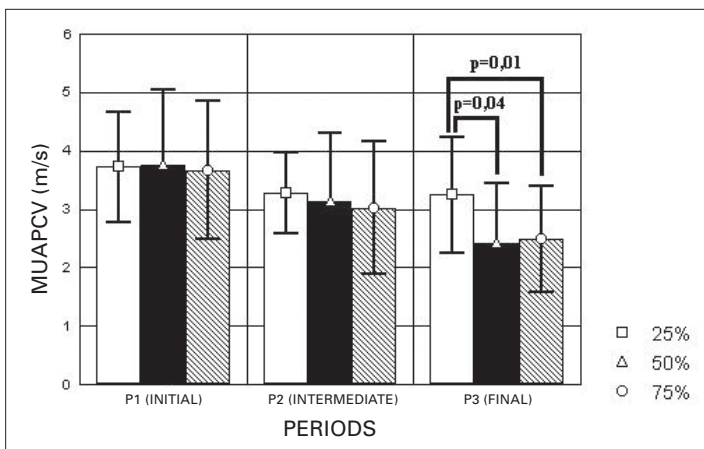


Fig. 5 – Average behavior of the MUAPCV (m/s) between periods (P1, P2 and P3) and between loads (25%, 50% and 75% of the ML) employed during tests.

DISCUSSION

The method proposed based on the use of simple adhesive surface electrodes for the estimation of MUAPCV allowed distinguishing satisfactorily the temporal behavior of this variable under different muscle contraction levels until exhaustion. Respecting norms with regard to the electrodes application, the method suggested presented advantages and simplicity that allows its reproduction at low costs, besides the application of a method for the calculation of the MUAPCV well described by literature and feasible from the computational point of view. However, once it does not deal about an invasive method, making use of the adaptation of a known method, the appraiser should be clear-sighted with regard to the

protocol of the electrodes application, mainly respecting the distance between them.

The decreasing temporal behavior between periods P1, P2 and P3 may be attributed to changes as result of a change on the intracellular pH due to the growth of ions H^+ , what would influence the functioning of the Na^+K^+ pumps and consequently the membrane permeability of the muscular cell. This process would cause, in turn, an unbalance on the concentration of these ions, leading to a decrease on the MUAPCV^(3,16). The literature also emphasize that the variable CMT would contribute for the installation of the fatigue, mainly after half of the total time spent in the task⁽¹⁵⁾, what could justify the MUAPCV behavior in periods P1 and P2 isolated, where no significant differences were observed between loads (figure 5). In this case, it is supposed that the variable TCM, considering periods P1 and P2, would have been sufficient to modify, only partly and therefore, not significantly, the permeability properties of the muscular fiber membrane.

With regard to the MUAPCV behavior at 50 and 75% of the ML, the results point to a worsening in the condition resulting of pH alterations previously discussed in function of the increase on NC, narrowing the blood flow even more and, therefore, the control of the metabolites growth^(17,18). The literature also reinforces the hypothesis that these cascade-type alterations would cause changes on the coupling process between myofilaments due to the incapacity of the sarcoplasmic reticule to release ions Ca^{2+} inside the muscular fiber, also involving the contractile mechanics, leading to a drop on the force production capacity^(17,19).

Another hypothesis establishes that the higher the NC and CMT are, the lower the blood perfusion capacity will be that, up to approximately 30% of the ML is still sufficient to avoid the rapid emergence of an ischemic situation in the tissue. Thus, it still would be possible to establish a balance, even not prolonged, at the intracellular pH level^(15,20). This theory meets what is observed at 25% of the ML, where no significant difference was found between periods, presenting no significant temporal drop in MUAPCV. On the other hand, Farina *et al.*⁽¹¹⁾, when estimated the MUAPCV of the anterior tibia muscle, found temporal decline of this variable with the maintenance of the isometric contractions in loads of 25%

REFERENCES

1. Dimitrova NA, Dimitrov GV. Interpretation of EMG changes with fatigue: facts, pitfalls, and fallacies. *J Electromyogr Kinesiol* 2003;13:13-36.
2. McComas AJ. Fatigue. In: *Skeletal Muscle – Form and function*. Human Kinetics, 1996.
3. Enoka RM, Stuart DG. Neurobiology of muscle fatigue. *J Appl Physiol* 1992;72:1631-48.
4. Latash ML. Fatigue. In: *Neurophysiological basis of movement*. Human Kinetics, 1998.
5. Hermens HJ, Freriks B, Merletti R, Stegeman D, Blok J, Rau G, et al. *European Recommendations for Surface Electromyography – SENIAM*, n. 8, 1999.
6. Broman H, Bilotta G, De Luca CJ. Myoelectric signal conduction velocity and spectral parameters: influence of force and time. *J Appl Physiol* 1985;58:1428-37.
7. Zennaro D, Läubli T, Krebs D, Klipstein A, Krueger H. Continuous, intermitted and sporadic motor unit activity in the trapezius muscle during prolonged computer work. *J Electromyogr Kinesiol* 2003;13:113-24.
8. Zijdwind I, Zwarts MJ, Kernell D. Fatigue-associated changes in the electromyogram of the human first dorsal interosseous muscle. *Muscle Nerve* 1999;22:1432-6.
9. Gantchev N, Kossev A, Gydikov A, Gerasimenko Y. Relation between the motor units recruitment threshold and their potentials propagation velocity at isometric activity. *Electromyogr Clin Neurophysiol* 1992;32:221-8.
10. Tokunaga T. Muscle fiber conduction velocity and frequency parameters of surface EMG during fatigue of the human masseter muscle. 1. Muscle fiber conduction velocity. *Nippon Hotetsu Shika Gakkai Zasshi* 1989;33:696-709.
11. Farina D, Arendt-Nielsen L, Merletti R, Graven-Nielsen T. Assessment of single motor unit conduction velocity during sustained contractions of the tibialis anterior muscle with advanced spike triggered averaging. *J Neurosci Methods* 2002;115:1-12.
12. Lowery M, Nolan P, O'Malley MJ. Electromyogram median frequency, spectral compression and muscle fibre conduction velocity during sustained sub-maximal contraction of brachioradialis muscle. *J Electromyogr Kinesiol* 2002;12:111-8.
13. Masuda T, Sadoyama T, Shiraishi M. Dependence of average muscle fibre conduction velocity on voluntary contraction force. *J Electromyogr Kinesiol* 1996;6:267-76.
14. Nishizono H, Saito Y, Miyashita M. The estimation of conduction velocity in human skeletal muscle in situ with surface electrodes. *Electroenceph Clin Neurophysiol* 1979;46:659-64.
15. Christova P, Kossev A, Kristev I, Chichov V. Surface EMG recorded by branched electrodes during sustained muscle activity. *J Electromyogr Kinesiol* 1999;9:263-76.
16. Fitts RH. Cellular mechanisms of muscle fatigue. *Physiol Rev* 1994;74:49-74.
17. Vøllestad NK. Measurement of human fatigue. *J Neurosci Methods* 1997;74:219-27.
18. Brody LR, Pollock MT, Roy SH, De Luca CJ, Celli B. pH-induced effects on median frequency and conduction velocity of the myoelectric signal. *J Appl Physiol* 1991;71:1878-85.
19. Murthy G, Hargens AR, Lehman S, Rempel DM. Ischemia causes muscle fatigue. *J Orthop Res* 2001;19:436-40.
20. Seals DR, Enoka RM. Sympathetic activation is associated with increases in EMG during fatiguing exercise. *J Appl Physiol* 1989;66:88-95.
21. Winter DA. *Biomechanics and motor control of human movement*. 2nd ed. Ed: John Wiley & Sons, Inc., 1990.
22. Gydikov A, Dimitrova N, Kosarov D, Dimitrov G. Influence of frequency and duration of firing on the shape of potentials from different types of motor units in human muscles. *Exp Neurol* 1976;52:345-55.

of the ML. Thus, it is suggested that the difference would lie on the fact that, despite the utilization of the verbal stimulus, part of the volunteers did not reach CMTs above values reached by some of the volunteers (above 3 minutes and a half), result also reflected in high standard deviation, equal to 113 seconds. It is believed that the high variability in the CMT at 25% of the ML may have occurred in function of the position suggested for the performance of tests that, for some volunteers, was defined as uncomfortable and, therefore, interrupted the test for not reaching an exhaustion condition, but rather for the discomfort with regard to the position adopted (figure 1).

Other variable considered as important but not evaluated is the motivation. It is important in the performance of different tasks, especially in long-duration tests and the hypothesis that it has influenced the results found at 25% of the ML is not rejected. Studies involving motivational aspects have been conducted with the objective of better understanding the mechanisms that act on endurance tasks, similar to those discussed in the present work^(2,3).

CONCLUSION

Some works have reported the importance of the MUAPCV as indicative of muscular fatigue when peripheral mechanisms are involved⁽¹¹⁾ and that it is possible to be measured through surface electrodes especially developed for this task. In the present work, an adaptation in the use of simple adhesive surface electrodes for the estimation of the MUAPCV was presented. These electrodes demonstrated to be of easy handling, low cost and the results obtained in the MUAPCV calculation were in agreement with those found in literature^(2,14,21,22). We are convinced that this methodology is practical and simple in the evaluation of this variable, important in the diagnosis and follow-up of pathological or non-pathological processes, which lead muscle to the fatigue condition.

All the authors declared there is not any potential conflict of interests regarding this article.
