33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

# Influence of Neuromuscular Electrical Stimulation on the Conduction Velocity Measured Using EMG Signals Provided by Linear Arrays of Electrodes

Kenia F. Pires, Leina A. B. Pimenta, Marcelino M. de Andrade, Diana G. Domingues, Cristiano J. M. R. Mendes, Adson F. da Rocha

*Abstract*— **Neuromuscular electrical stimulation (NMES) can alter the functioning of muscles and even assist muscle rehabilitation. In this paper, we evaluate the effect of NMES on the conduction velocity (CV) of the brachial biceps' motor units. We used a linear array of electrodes to acquire electromyographic signals, as different subjects perform isometric voluntary contractions (IVCs),with and without prior NMES. Our results show that, after NMES, the CVs at the beginning of the IVCs tend to increase, with respect to the case without NMES. Also, we observed that, while in the absence of NMES, the CVs tend to decrease over time with continued IVCs, this does not happen after 20 minutes of NMES, and the CVs can, in some cases, increase with the contractions.**

## I. Introduction

NEUROMUSCULAR electrical stimulation (NMES) can affect muscle functioning by using electrical potentials that reach the muscular tissues through the peripheral nervous system [1]. This procedure can be done in a noninvasive manner, by positioning a set of electrodes over the muscle belly. In this paper, we evaluate the impact of a low frequency NMES protocol on the motor units' conduction velocity (CV), an important electromyographic variable used, among other applications, to assess muscle fatigue.

In applying the NMES, the standard procedure is to successively apply a sequence of cycles, each including two intervals of the order of a few seconds. The first interval of each cycle corresponds to the stimulation stage, in which the stimulation potential is applied to the muscle, thus leading to contraction. In the second interval, the stimulation is suspended in order to allow muscle relaxation. The whole process of contraction and relaxation is repeated for several minutes, the total duration of the NMES. In this research, we analyze the resulting measured CVs immediately after the whole NMES period, when the subject is conducting a normal voluntary isometric contraction and compared to the same activity without previous NMES.

The effect of the electrical stimulation in each cycle's stimulation interval is to recruit motor units according to the reverse size principle, according to which larger units are recruited first, followed by the smaller, slower units [2-5]. The reason is based on the fact that the axons belonging to the faster motor units present lower resistance and thus conduct the action potentials at higher rates, when compared to the axons belonging to the smaller motor units. Also note that premature muscle fatigue is commonly related to the use of NMES.

In order to measure the motor unity CVs, we collected surface electromyographic (EMG) signals. The electromyography is a standard technique for monitoring and capturing the recruitment of motor units during voluntary contractions, which can be affected by anatomic and physiological muscle characteristics [3]. An important application of surface EMGs is the detection and analysis of muscle fatigue, defined as a temporary loss of strength [4], [5]. In fact, several EMG properties are indicators of fatigue, including the root mean square (RMS), the mean power frequency (MPF) and the conduction velocity (CV) [6]. In this paper, we positioned the EMG electrodes in the direction of the muscle fiber, and determined the time delay between two EMG signals in order to estimate the CV [7].

The choice of linear arrays of electrodes was motivated by two aspects: (1) this arrange favors the adaptation to the geometric and anatomic properties of the motor units, as well as the proper location of the innervation zone (IZ) and the ideal location where to position the detection electrode; (2) it provides high resolution when estimating the motor unit's CV [8], [9].

## II. Methodology

The experimental procedures took place in the Biomechanics Laboratory at the University of Brasília (UnB). They were previously approved by the Research Ethics Committee of the UnB College of Medicine, according to report CEP-FM 049/2009. Also, each elaboration and execution stage followed the recommendations from the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM).

The testing sample included 10 healthy men, with average ages, weights, and heights given, respectively, by (22.92 ± 2.98) years old, (75,15 ± 10,40) kg and (1,78 ± 0,51) m. After we described the procedures in details, the subjects signed the informed consent forms.

The experimental procedures were divided into two main

Manuscript received April 15, 2011.

K. F. Pires and L. A. B. Pimenta are with the Faculty of Medicine, University of Brasilia, Brazil.

A. F. Rocha (corresponding author – phone: +55-61-3107-8201, email: adson@unb.br), M. M. Andrade, D. G. Domingues, and C. J. M. R. Mendes are with the University of Brasilia at Gama, Federal District, Brazil.

stages:
- In the first day, each subject performed an isometric voluntary contraction (IVC) at 60% of the maximum isometric voluntary contraction (MIVC), without previous NMES.
- Three days later, we submitted the same subjects of the first stage to 20 minutes of NMES and, immediately after that, they performed an IVC at 60% of the MIVC.

In each of these stages, we conducted the following procedures in order to properly position and fix the linear arrange of electrodes and prepare for the main tests:

**1.** Skin asepsis in the inner region of the subject's dominant arm, followed by trichotomy using disposable blades.
**2.** Determination of the MIVC based on the average of two measurements.
**3.** Positioning of a semiflexible linear array of electrodes over the subject brachial biceps, in the dominant arm. We used electrode arrays configured as 10 mm by 1 mm bars, and printed over a flexible tape with a 5 mm distance between consecutive electrodes.
During this procedure, in order to map the IZ, we asked the subjects to perform, for 5 seconds, an IVC at 30% of MIVC. After collecting the corresponding EMG signals, we identified the IZ by locating the channel with a phase inversion, with respect to the previous channels. As an example, in Figure 1 we observe a phase inversion in channel 8, which corresponds to the location of the IZ. Also, in this case the position where to fix the array of electrodes corresponds to the inside region between channels 9 and 14, as this contains the signals with phase delays and high amplitudes.
**4.** Fixing of the linear flexible array over the skin, in the region determined in the previous stage, and application of the conductor gel on the electrodes.

Once we properly fixed the electrodes, we conducted the experimental procedures detailed below.

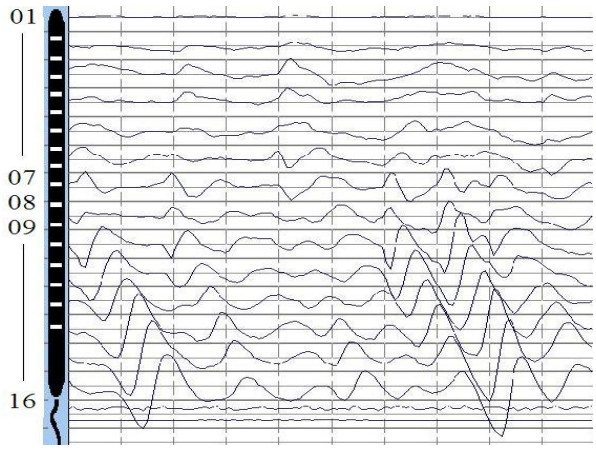


**Figure 1.** Electromyographic signals from 16 channels, used to locate the innervation zone (IZ) and the region where to collect the electromyographic signals using the linear array of electrodes.

### Experimental procedures in the first day

In the first day, we registered the EMG signals and the force signals as the subjects performed, until exhaustion, an IVC at 60% of the MCIV, without previous NMES (day1). In these measurements, we used, respectively, the previously described linear array of electrodes and a TS model cell load with 50 kgf of maximum load. Figure 2 shows the basic configuration, with an adapted common chair where the subject stayed sat. Note that we connected the load cell to a hand wood device; the subject was required to hold this wood device in order to perform the contractions. Also observe the chair welded to a steel vertical bar of adjustable height and with an arm support, so that the subject's forearm would be well supported with his elbow at 90 degrees, as he performed the IVC.

**Figure 2.** Part of the experimental equipment and positioning of the subject, as he performed the isometric voluntary contraction (IVC). Note the chair, the arm support welded to the chair, the load cell, and the hand wood device.

### Experimental procedures three days later

Three days after stage 1, we conducted the tests to evaluate the effect of NMES on the measured CVs. For applying the stimulation electrical potentials, we used the electrostimulator Dualpex 961, registered at the Brazilian National Sanitary Agency (Anvisa) under number 80079190004. The used electrodes are made of silicon carbide (SiC), and are fixed to the subject's skin using adhesive tape and conductive gel to reduce resistance.

The NMES electrodes were positioned on the brachial biceps' IZ. The subjects received the electrical stimulation according to the NMES protocol in Table 1. Note that the stimulation took, for each subject, 20 minutes, which were divided into cycles of 14 seconds of stimulation plus 10 seconds of rest, when the stimulation was suspended to allow muscle relaxation until the next cycle.

Table 1: Physical parameters of the used NMES protocol

| NMES physical parameters | Value |
|---|---|
| Waveform | Bipolar |
| Frequency | 50 Hz |
| Pulse width | 250 μs |
| Rising time | 2 seconds |
| Sustaining period | 10 seconds |
| Fall time | 2 seconds |
| Rise time | 10 seconds |
| Ratio between $T_{on}$ and $T_{off}$ | 1:1 |
| Total stimulation time | 20 minutes |

Immediately after the 20 minutes of NMES, the subjects performed again an IVC at 60% of MIVC, until exhausted. We recorded the force and EM signals using the same equipment of stage 1.

In Figure 3, we show the positioning of the NMES electrodes, impregnated with conductive gel and fixed with adhesive tape to the center of the brachial biceps' innervation zone.

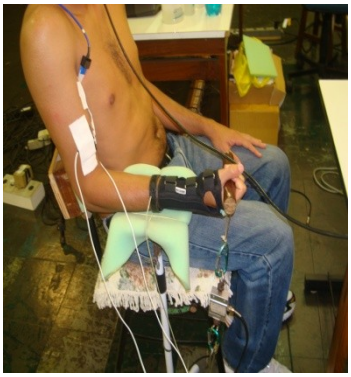

**Figure 3.** Subject wearing the fist orthesis, the wood hand device fixed to the cell load, the flexible linear array of electrodes, and the SiC electrodes used for the NMES.

## III. Processing of the Obtained EMG Signals

After collecting the EMG signals in the first day (no NMES) and three days later (with NMES), we selected a 30-second window from each signal. In fact, for this considered time interval, the observed CVs could be appropriately modeled as a linear function of time, and we analyzed the behavior of this function with respect to the presence or absence of a previous NMES.

For each acquired signal, we computed the CVs by using the method of maximum likelihood [10]. We then performed a first-order linear regression procedure, in order to model the measured CV data as a linear function of time; we adopted here the method of minimizing the least square error between the measured data and the linear model.

Note that the slope of the line, after the linear regression procedure, provided the rate at which the VCs changed with time, whereas the intersection between the line and the dependent variable axis provided the initial value of the VC.

## IV. Results

Using the method described in Section III, we computed, for each of the 10 subjects in the experiment, the initial CV ($CV_0$) and the rate at which the CV changed with time (incCV), during the considered interval and according to the linear model obtained by linear regression. Table 2 shows the corresponding values, without and with previous NMES (days 1 and 3, respectively). Note that also shown are the values of the same rates, normalized by the initial values of the CVs. Furthermore, we indicate all the values as averaged for the 10 subjects.

Observe that, after the NMES, most of subjects had an increase in the CV, and only the subjects 5 and 10 had a small decrease. However, the average $CV_0$ increased from 4.992 m/s to 5.473 m/s. In order to check if this increase has statistical significance, we applied two paired test: the *Lilliefors*, to check for a gaussian distribution (p = 0.3515) and the *t-student* test (p = 0.0492). The *Lilliefors* test showed that the it is reasonable to treat the distribution as Gaussian, and the *t-student* test led to a result that is at the threshold that indicates a statistically significant difference between the two results.

**Table 2.** Measured initial values of the conduction velocities ($CV_0$), rates of CV change with time (incCV) and corresponding rates normalized by the initial values (NincCV = incCV/$CV_0$), as measured in days 1 and 3 for the 10 considered subjects.

| | Day 1 (no NMES) | | | Day 4 (with NMES) | | |
|---|---|---|---|---|---|---|
| **Subject** | **$CV_0$ (m/s)** | **incCV (m/s/s)** | **NincCV (1/s) (incCV/$CV_0$)** | **$CV_0$ (m/s)** | **incCV (m/s/s)** | **NincCV (1/s) (incCV/$CV_0$)** |
| **1** | 4.869 | -0.0047 | -0.00096529 | 5.714 | 0.0012 | 0.00021001 |
| **2** | 5.151 | -0.0531 | -0.01030868 | 5.952 | -0.0581 | -0.00976142 |
| **3** | 4.864 | -0.0015 | -0.00030839 | 5.247 | -0.0084 | -0.00160091 |
| **4** | 5.343 | -0.0074 | -0.00138499 | 5.568 | -0.0271 | -0.0048671 |
| **5** | 4.567 | -0.0077 | -0.00168601 | 4.14 | -0.0016 | -0.00038647 |
| **6** | 5.057 | -0.0071 | -0.00140399 | 5.437 | 0.0098 | 0.00180246 |
| **7** | 4.417 | 0.0148 | 0.003350691 | 6.379 | 0.06621 | 0.01037937 |
| **8** | 4.392 | -0.0062 | -0.00141166 | 4.941 | -0.0032 | -0.00064764 |
| **9** | 5.940 | -0.0482 | -0.00811448 | 6.397 | -0.0914 | -0.01428795 |
| **10** | 5.315 | -0.0218 | -0.0041016 | 4.958 | 0.01532 | 0.00308996 |
| **Average** | 4.992 | -0.014 | -0.003 | 5.473 | -0.010 | -0.002 |
| **Standard Deviation** | 0.478 | 0.021 | 0.004 | 0.695 | 0.043 | 0.007 |

Regarding the observed slopes of the CV curves associated with the fatigue due to voluntary contraction with and without the NMES procedure, in order to test the statistical significance of the measured values of NincCV, we applied, for day 1, the unpaired *Lilliefors* (to check for a gaussian distribution) and the *Wilcoxon* tests; the obtained statistical significances were, respectively, p = 0.0144 (i. e. non-gaussian distribution, leading to the use of the Wilcoxon [non-parametric] test) and p = 0.0371 (indicating a mean negative slope that is statistically significant). For the third day, we applied the *Lilliefors* and the *t*-student (since the distribution was found to be gaussian) tests, with statistical significances of, respectively, p = 0.3045 and p = 0.4764.

## V. Discussion

The experiments provided some relevant results. The first refers to the measured initial value of the motor units' conduction velocity ($CV_0$) after the NMES, when compared to the same value without NMES. At day 1, when no NMES was used, we measured the $CV_0$ as the subjects performed as IVC at 60% of the MIVC. At day 4, before repeating the same test, we conducted 20 minutes of NMES before measuring the $CV_0$. The results showed that the NMES increased the initial conduction velocity, as the value of $CV_0$ measured in day 4 was significantly higher than in day 1.

This result provides important information in terms of the difference between voluntary contraction and contraction elicited by NMES. In fact, in a situation of voluntary contraction, what we expect is that the conduction velocity reduces with time. In this case, after 20 minutes of voluntary

contraction (compared to 20 minutes of NMES, as we did in day 4), the CV is expected to be lower than at the beginning of the contractions. However, in our experiments, after 20 minutes of contraction caused by NMES, the conduction velocity in fact increased, with statistical significance ($p = 0.049$), according to the t-student test we performed.

Another relevant result we obtained relates to the slope of the line corresponding to the linear regression model for the CV (this inclination describes the rate at which the CV changes with time). A known fact about the CV is that it normally decreases with time, during isometric contractions. This result was confirmed by the first day of the experiment, when we observed, with statistical significance ($p = 0.037$), the tendency of a negative inclination (we consider that the brachial biceps muscle has high tendeny to muscle fatigue, due to the concentration of type II fibers – 57.7% in the superficial layer and 49.3% in the inner layer). However, we observed, in day 4, that this behavior does not occur if the same IVC protocol is performed after the NMES. In this case, 60% of the measured data showed negative inclination, but 40% showed positive inclination. In fact, the data indicate that there is no statistically significant tendency for a negative or positive slope ($p = 0.4764$). Therefore, our results suggest that the previous NMES significantly altered the behavior of the CV during an IVC at 60% of the MIVC.

There are some possible hypotheses to explain these changes. For example, the NMES may have caused some kind of degradation to the electrodes and to the conductor gel used in the experiment. We believe, however, that these effects are due to a change in recruitment pattern during contraction. Note that the normal behavior is that, initially, faster fibers are recruited during contraction and, as the contraction continues, their efficiency decreases and other fibers, with gradually lower conduction velocities, start to be recruited as well. As a result, the lower action potentials of the slower fibers contribute to reduce the average velocity [2], [11]. In this context, it is possible that previous NMES modifies this normal recruiting behavior, in such a way that the muscle fibers start to be recruited in a different order, when compared to the case without previous NMES. Under this condition, the slower fibers would be recruited first, then lose their mechanical efficiency, so that the faster fibers would then be recruited and thus leading to an increase of the CVs over time. We emphasize that this is still only a hypothesis, which must be tested in more detail before it is accepted or refuted.

## VI. Conclusion

In this paper, we evaluated the effect of neuromuscular electrical stimulation (NMES) on the conduction velocity (CV) of the brachial biceps' motor units. In particular, we measured the initial CVs as the subjects performed isometric voluntary contractions (ICVs), without and with previous NMES. We also measured the rate at which the CVs changed over time, during ICVs, after NMES and without NMES.

Our results show, with statistical significance, an increase in the CV right after NMES and as the ICVs start, opposed to the ICVs without prior NMES.

We also observed that, without NMES, the CVs tend to decrease with continued IVC, as commonly seen in the literature; however, after NMES and for about half of the subjects, the CVs actually tended to increase over time with continued IVC (during the analyzed intervals).

Among the possible explanations we considered, the most plausible to us seems to be that the NMES modifies the recruitment pattern of motor units during the contractions. According to this hypothesis, NMES would cause slower motor units (with lower ICs) to be recruited before the faster ones, as opposed to what happens in the absence of NMES. A detailed investigation of this hypothesis in an interesting possibility for a future related work.

## Acknowledgment

The authors thank the Center for Sports Excelence (CENESP), the Laboratory of Biomechanics and Biological Signal Processing, and the College of Physical Education of the University of Brasilia. We also thank CNPq and CAPES (brazilian funding agencies) for the financial support.

## References

[1] Minimum required skills of physical therapist graduates at wntry-level. http://www.apta.org/ Acessible on 03/20/2011.

[2] C. M. Gregory, C. S. Bickel. "Recruitment patterns in human skeletal muscle during electrical stimulation," *Physical Therapy*, vol. 85, no. 4, pp. 358-364, 2005.

[3] C. J. De Luca, A. Adam, R. Wotiz, L. D. Gilmore and S. H. Nawab "Decomposition of surface EMG signals," *Journal of Neurophysiology*, vol. 96, p. 1646-1657, 2006.

[4] S. K. Stackhouse, D. S. Reisman and S. A. Binder-Macleod. "Challenging the Role of pH in Skeletal Muscle Fatigue," *Physical Therapy*, vol. 81, no. 12, pp. 1897-1903, 2001.

[5] S. A. Binder-Macleod, D. W. Russ. "Effects of activation frequency and force on low-frequency fatigue in human skeletal muscle,"*J. Appl. Physiol*., vol. 86, no. 4, pp. 1337-1346, 1999.

[6] D. Farina, D. Zennaro, M. Pozzo, R. Merletti and T. Läubli. "Single motor unit and spectral surface EMG analysis during low-force, sustained contractions of the upper trapezius muscle," *European Journal ofApplied Physiology*, vol .96, pp. 157-164, 2006.

[7] R. Merletti, D. Farina and M. Gazzoni. "The linear electrode array: a useful tool with many applications," *Journal of Electromyography and Kinesiology*, vol. 13, pp. 37-47, 2003.

[8] D. Farina, P. Madeleine, T. Graven-Nielsen, R. Merletti and L. Arendt-Nielsen. "Standardising surface electromyogram recordings for assessment of activity and fatigue in the human upper trapezius muscle," *European Journal of Applied Physiology*, vol. 86, pp. 469-478, 2002.

[9] R. Merletti, D. Farina and A. Granata. "Non-invasive assessment of motor unit properties with linear electrode arrays," *Electroencephalography and Clinical Neurophysiology*, vol. 50, pp. 293-300, 1999.

[10] D. Farina and R. Merletti. "Comparison of algorithms for estimation of EMG variables during voluntary isometric contractions," *J. Appl. Physiol*., vol.10, pp. 337-349, 2000.

[11] M. Merletti, M. Knaflitz, C. J. DeLuca. "Myoelectric manifestations of fatigue in voluntary and electrically elicited contractions," *J. Appl. Physiol*., vol. 69, no. 5, pp. 1810-1820, 1990.

[12] R. Merletti and P. A. Parker. "Electromyography – Physiology, Engineering, and Noninvasive Applications". *IEEE Press Engineering in Medicine and Biology Society*, Sponsor, p.19-21.