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Syncronicity relationship between the mechanomyography peak energy frequency and the maximum electrically evoked contraction in paraplegics

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Abstract— **The goal of this paper is to investigate the temporal-spectral decomposition content during a maximal electrically evoked contraction (MEEC) in two spinal cord injured participants using triaxial mechanomyography (MMG). Two male spinal cord injured volunteers performed the tests both injured at T7 neurologic level. The triaxial MMG signal of *rectus femoris* muscle was processed with Cauchy wavelet transform adjusted to third-order 5-50 Hz bandpass Butterworth filter. A custom electrical stimulator voltage-controlled was configured: pulse frequency set to 1 kHz (20% duty cycle) and burst (modulating) frequency set to 70 Hz (20% active period). The MEEC force was performed by increasing the electrical stimulating magnitude (~3 V/s to avoid motoneuron adaptation/habituation) until the force started to level off. We conclude that the peak energy of MMG signal frequency did not occur simultaneously with the maximal electrically evoked contraction to *rectus femoris* muscle. Moreover, the vibration vector of muscle, expressed in three axes (X, Y and Z), presented different fired frequencies, mainly between X (transverse) and Z (perpendicular) axis, where the frequencies fired by Z axis were greater.**

I. Introduction

One of the techniques inside the physical rehabilitation area is functional electrical stimulation (FES) that artificially activates the neural pathways present in nerve fibers of neuromuscular tissue to produce a functional contraction. Regarding the design of neural prosthesis control systems aiming to promote (FES-aided) assistive locomotion or even during physical rehabilitation applied to spinal cord injured patients, the myofibers mechanical vibration information content can be used for evaluating the muscular condition. This technique, known as mechanomyography, does not suffer direct interference by FES. A triaxial MMG sensor is built with a triaxial accelerometer that registers myofibers vibrations in three orthogonal directions [1]. However, Archer et al. [2] studying different levels of maximal voluntary contraction in able-bodied volunteers observed spectral differences between longitudinal and perpendicular axes. Therefore, using sensors able to measure the muscle vibration in three directions can determine whether there are relationships in other directions.

The goal of this paper is to investigate the MMG temporal-spectral decomposition content during a maximal non-voluntary electrically contraction in two spinal cord injured participants among three cardinal planes.

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II. Methods

A. Volunteers

This work was approved by the *Secretaria de Saúde do Estado do Paraná* Research Ethics Committee n° 189/2010 according to the Helsinki Declaration of 1975, as revised in 1983. Two male spinal cord injured volunteers performed the tests (1 and 2) both injured at T7 neurologic level, ranked as level A (without motor or sensorial function below the lesion level) in American Spinal Injury Association (AIS) using baclofen® to regulate muscular tonus. The demography was considered equivalent in relation to age (34 and 25 yrs), body mass (60 and 62 kg), stature (1.75 and 1.73 m), thigh skinfold thickness (18.8 and 9.2 mm) and time of injury (18 and 9 months) to 1 and 2, respectively. During the protocols, the room temperature varied from 24.4 to 25.9 ºC and humidity from 51 to 65% and spastic events did not jeopardize the tests.

B. Electrical Stimulation Parameters

A custom electrical stimulator produced monophasic rectangular wave with voltage-controlled stimulation pulses. The electrical stimulator had a stimulation security limit of 250 V. The parameters were set to: pulse-frequency set to 1 kHz (20% duty cycle, 200 µs pulse-duration) and burst (or modulating) frequency set to 70 Hz (20% active period). The self-adhesive electrodes were of different sizes and were positioned on the thigh over the knee region (anode with 5 x 9 cm) and over the femoral triangle (cathode with 5 x 5 cm) to stimulate the quadriceps muscle via femoral nerve.

C. Register of muscular vibration and force

The developed MMG sensor used Freescale MMA7260Q MEMS triaxial accelerometer (13x18 mm, 0.94 g) with sensitivity equal to 800 mV/G at 1.5 G (G: gravitational acceleration). Electronic circuits allowed 2.2x amplification.

An S-shape aluminum body load cell (50 kgf ≈ 500 N) with four strain gages in full Wheatstone bridge measured

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the force produced.

The MMG sensor was positioned on *rectus femoris* (RF) muscle belly using double-sided adhesive tape. The sensor placement was equidistant between the anterosuperior iliac spine and base of *patella* bone.

The load cell was attached on the distal third of volunteer's leg through band strips and a Velcro strap belt stabilized the trunk as illustrate in Fig. 1.

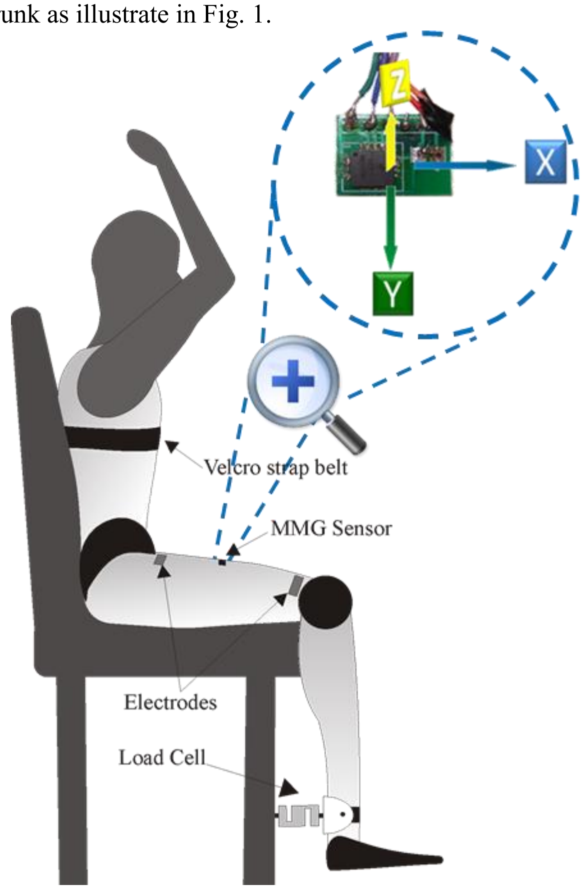

Figure. 1. Instrumentation layout. MMG sensor axes: X (transverse), Y (longitudinal) and Z (perpendicular).

D. Data acquisition

A LabVIEW™ program was coded to acquire MMG signals. The acquisition system contained a NI-USB 6221 National Instruments™ board working at 1 kHz sampling rate.

E. Research Design

The subject was positioned on the chair with the hip and knee fixed to 70° of flexion. The skin was shaved and cleaned; it was obtained the anthropometrical parameters and osteomuscular warm-up with fifteen passive knee mobilizations. After the placement of the FES electrodes on the left limb, a minimum of 10 min rest time was respected to provide skin-electrode impedance balance.

One maximal electrically evoked contraction (MEEC) force was performed by increasing the electrical stimulating magnitude (approximately 3 V/s to avoid motoneuron adaptation/habituation) until the force started to level off.

F. Data Processing and Analysis

The signal was processed by custom-written MatLab® software version R2008a. The total time between the onset of contraction and the leveling off force was processed to X (transverse), Y (longitudinal) and Z (perpendicular) axes (to anatomical position). The MMG signal was processed with a third-order 5-50 Hz bandpass Butterworth filter. We processed the MMG signal using the Cauchy wavelet (CaW) transform [3]. The decomposition in wavelet bands was defined by equation 1, being f: frequency, f_c: center frequency, s: scale factor, q=1.45, r=1.959 and j: center frequency level.

$$f_c(s,j) = \frac{1}{s}(j+q)^r \tag{1}$$

The parameters in Eq. (1) were adjusted with s= 4 and j=21(0-20) to characterize the acquired MMG signal using electrical stimulation. From j=21(0-20), we chose twelve frequencies (between 4.6 and 53.3 Hz) where each CaW band point (x) was rectified (x = |x|). Force was calibrated to initiate in 0 kgf.

III. Results

The MEEC and electrical stimulator intensity (in parenthesis) were 5.27 kgf (170 V) and 17.62 kgf (115 V) to A and B, respectively. Figs. 2 and 3 show that to both participants, 1 and 2, respectively, the peak of energy did not occur simultaneously with the MEEC, as represented by reddish colors in the color scale. The energy frequency concentration to X-axis was lower than Z-axis for both participants. Even with lower FES intensity, the volunteer B achieved greater force (17.62 kgf) than volunteer 1 (5.27 kgf), consequently, the frequencies fired to volunteer 2's muscle fibers were greater than 20 Hz (both participants were stimulated with 70 Hz modulated frequency).

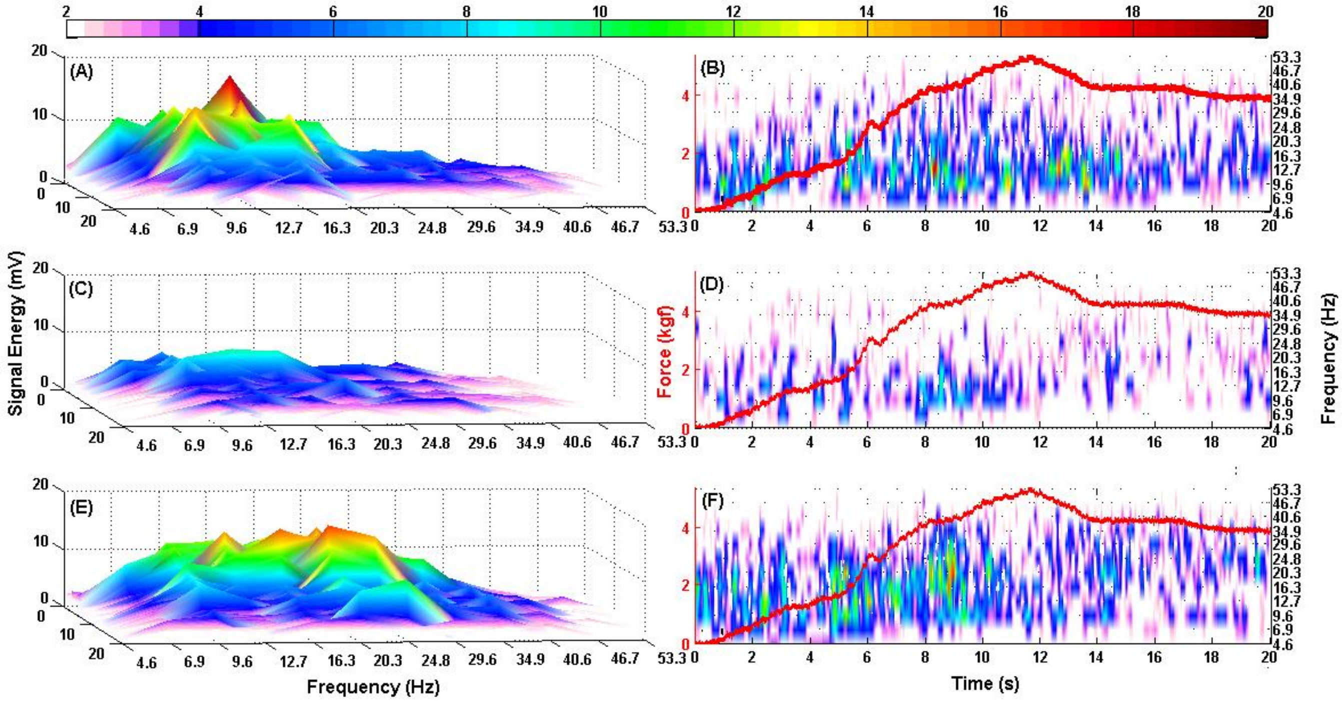

Figure. 2. 3D (A, C and E) and 2D (B, D and F) MMG time-frequency responses during maximal electrically stimulated contraction to volunteer 1. A and B: X-axis, C and D: Y-axis, E and F: Z-axis. The color bar shows the maximum value (among X, Y and Z-axes) in dark red color and the values below 10% of maximum (among X, Y and Z-axes) are in white color. Force: red line in 2D image.

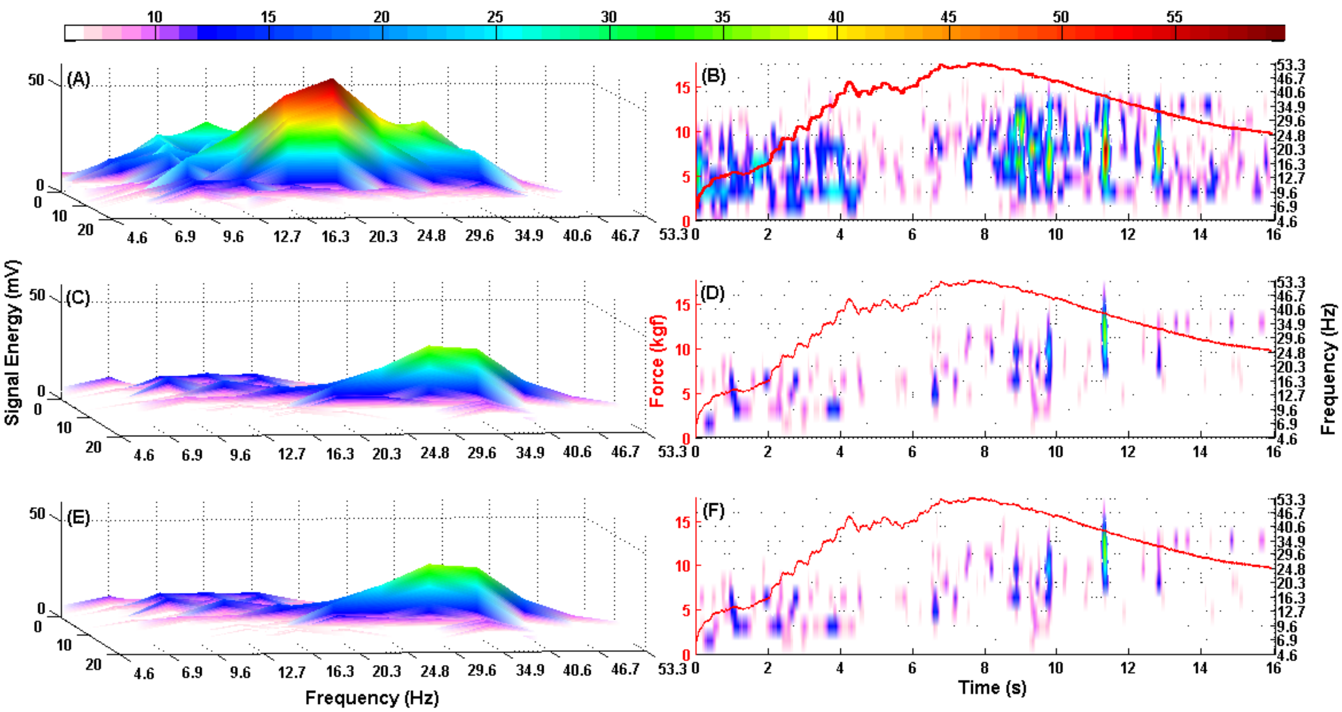

Figure. 3. 3D (A, C and E) and 2D (B, D and F) MMG time-frequency responses during maximal electrically stimulated contraction to volunteer 2. A and B: X-axis, C and D: Y-axis, E and F: Z-axis. The color bar shows the maximum value (among X, Y and Z-axes) in dark red color and the values below 10% of maximum (among X, Y and Z-axes) are in white color. Force: red line in 2D image.

IV. Discussion

Our study evaluates the increase of force since relaxed muscle (0% MEEC) until the peak of force (100% MEEC). On the other hand, to discuss our paper we ended up using other researches that investigate different levels of voluntary and non-voluntary contraction.

Archer et al. [2] studying levels of maximal voluntary contraction in able-bodied volunteer punctuated that the Y-axis (longitudinal) vibrates with frequencies greater (25 Hz or above) than Z-axis (perpendicular). This relation was not found in our study, mainly because the Z-axis energy vibration is lower than X and Y axes for the first participant (Fig. 2) and similar between Z and X axes (Fig. 3).

Our work differs from other studies (Archer et al. [2] Orizio et al. [4, 5] Orizio et al. [4] Miyamoto and Oda [6]) on: (a) the physiological difference between muscles (Andersen et al. [7], Burnham et al. [8] and Talmadge et al [9]), since paraplegic's muscles tend to change in the proportion of fast/slow fibers due to predominantly hypotrophy/atrophy of slow fibers; and (b) the data analysis method adopted (CaW), which enables us to observe the frequency shifter during the protocol. In the (a) case, it was expected that the vibration frequency would tend to decrease quickly during the fatigue condition observed along the time in Figs. 2 and 3 for all axes.

Orizio et al. [5] concluded that MMG RMS value (MMG_{RMS}) increases at low levels of effort due to the probable recruitment of new motor units. At high levels of effort, MMG_{RMS} decreases and the hypothesis to explain it is the reduction on the recruitment of fast (glycolytic) fibers possibly due to muscular fatigue. However, it was noticeable with our participants that the peak of energy did not occur during the MEEC.

Orizio et al. [4] recorded MMG from *gastrocnemius* muscle of cat and showed that the muscular oscillation amplitudes, expressed by temporal feature root mean square (related to the energy of signal), were positively correlated to the increase of muscle strength. The present study shows (Figs. 2 and 3) that the peak energy of MMG frequency content did not occur simultaneously with the MEEC to *rectus femoris* muscle, even though Ohta et al. [10], investigating medial gastrocnemius muscle performance at different levels of maximum voluntary contraction (MVC), showed that MMG amplitude presents a linear decrease at levels up to 80% of the MVC. However, Stock et al. [11] found that above 80% of MVC there is a decay in the amplitude of MMG temporal domain responses of *rectus femoris* muscle during concentric movements. Therefore, our results are in accordance with their data.

Miyamoto and Oda [6] evaluated the triceps *surae* muscle (N=8) during MVC with MMG (microphone sensor-uniaxial) in different degrees of knee flexion (60 to 180° (full extension)) of able-bodied volunteers. In their study, the mean power frequency remained unaltered (between 10-18 Hz) during MVCs with knee angle joint variations. This displacement axis is related to the Z-axis (perpendicular). However, in our study the participant B achieved frequencies above 20 Hz, this event can be explained due the accelerometer is better sensor than microphone to register the myofiber vibration.

V. Conclusions

In this preliminary investigation, with two spinal cord injured participants, we conclude that the peak energy of mechanomyography signal frequency does not occur simultaneously with the maximal electrically evoked contraction to *rectus femoris* muscle. Moreover, the contribution of each component of the muscle vibration vector (X, Y and Z) presents different muscle firing frequencies in an interaxial comparison, mainly between X- (transverse) and Z- (perpendicular) axis, where the frequencies fired by Z-axis were greater.

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