Mechanomyography energy decreases during muscular fatigue in paraplegics

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***Abstract*— The present work investigated the response of triaxial MMG signals acquired from the rectus femoris muscle of spinal cord injured volunteers during fatigue protocol electrically evoked. A custom functional electrical stimulator voltage-controlled was configured as: pulse frequency set to 1 kHz (20% duty cycle) and burst (modulating) frequency set to 70 Hz (20% active period). The triaxial MMG signal of *rectus femoris* muscle was processed with third-order 5-50 Hz bandpass Butterworth filter and the values were normalized. A load cell was used to register the force. The stimulator output voltage was increased until the maximal electrically-evoked extension (MEEE) of knee joint. After the load cell placement, the stimuli magnitude required to reach the MEEE was applied and registered by the load cell as muscular force-100% response. Stimuli intensity was increased until and during the control to keep the force in force-100%. Four instants with force functional electrical stimulation (FES)-controlled were selected between force-100% and slope down to force-30%. The MMG energy decreased with FES application due neuromuscular fatigue in paraplegic subjects. X-axis between instant I (1 ± 0) and instant IV (0.74 ±0.27), and the same tendency was found to Y-axis between instant II (1.14 ± 0.44) and instant IV (0.91 ± 0.3).**

I. Introduction

Due to the inability of voluntary lower limb contraction, paraplegics consider a challenge to perform sit-to-stand movements and maintain balance standing [1].

Although there is no technique to naturally generate physiological contraction on their handicapped lower limbs, studies investigated the use of implanted functional electrical stimulation neuroprostheses. With this aim, Guiraud et al. [2] in their case report, showed the effects of nine years using a neuroprosthesis and concluded that muscle fatigue is a major issue for the future. At the end, they suggest more studies focusing on neural stimulation efficiency.

In order to get such efficiency it is necessary to avoid muscle fatigue induced by electrical stimulation [2]. However, how to avoid something that is not clear when it happens?

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Previous studies applying mechanomyography showed the feasibility to measure and monitor mechanical muscle oscillations during electrically elicited contraction during fatigue protocols [3]. Therefore, the goal of the research discussed in this paper is to verify the MMG energy response in *rectus femoris* muscle of paraplegic participants during electrically-evoked isometric contractions and a fatigue protocol.

II. Methods

A. Participants

This work was approved by *Secretaria de Saúde do Estado do Paraná´s* Research Ethics Committee according to the protocol number 189/2010 and in conformity with Helsinki Declaration of 1975, as revised in 1983. The patients inclusive criteria were: spinal cord injury without voluntary contraction on quadriceps muscle. The patients exclusive criteria were: cancer in the lower limb (stimulated area), participants who have been submitted to X-ray examination in the last two weeks (aversion), with metal implanted in the stimulated limb, cognitive impairment or without toleration to FES sensation. The protocol flowchart is shown in Fig. 1. During the clinical research sessions, the environment temperature and moisture were 31.4 ± 2.28 ºC and 43.4 ± 10 %, respectively. Spastic events and medicines to regulate the muscular tonus did not jeopardize the tests. The sample demography is shown in Table I. All of them were ranked on American Spinal Cord Injury Association Impairment Scale A or B, without voluntary contraction in lower limbs.

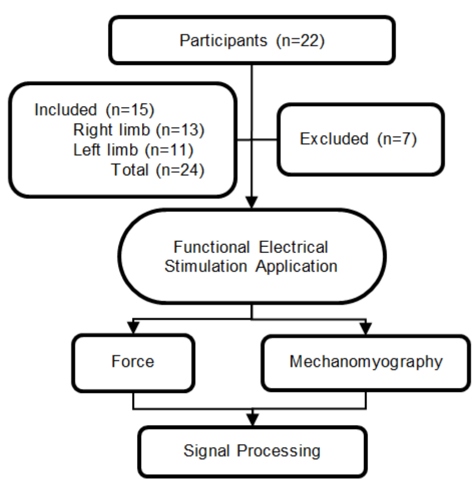

Figure. 1. Protocol flowchart.

TABLE I
PARTICIPANTS DEMOGRAPHY

Part	Age (yrs)	Weight (kg)	Height (m)	Spinal cord injury Level	Time	Etiology
1	34	60	1.75	T7	16 ms	Auto
2	25	62	1.73	T7	9 ms	Violence
3	25	65	1.89	T6-7	5 yrs	Violence
4	26	80	1.82	C7	1 yr	Dive
5	24	86	1.74	T6-7	2 yrs	Auto
6	19	70	1.86	T7	2 yrs	Violence
7	27	90	1.7	T6	2 yrs	Auto
8	21	87	1.78	T7	19 ms	Auto
9	34	75	1.7	T5-6	2 yrs	Auto
10	33	80	1.81	C5	2 yrs	Auto
11	29	80	1.83	T10-11	2 yrs	Violence
12	22	60	1.69	T7-10	3 yrs	Auto
13	24	77	1.89	C5	20 ms	Auto
14	29	76	1.79	T3-5	17 yrs	Violence
15	35	89	1.73	L10	28 ms	Fall

yrs: years, ms: months

B. *Electrical Stimulation Parameters*

A custom electrical stimulator produced monophasic rectangular wave with voltage-controlled stimulation pulses. The parameters were set to: pulse frequency set to 1 kHz (20% duty cycle) and burst (or modulating) frequency set to 70 Hz (20% active period). The self-adhesive electrodes had 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. *Sensors*

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 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. 2. Research Design

1) *Pre-protocol*

The subject was positioned on the chair with the hip and knee fixed to 70° of flexion. The skin was shaved and cleaned; anthropometrical parameters were obtained and performed passive knee mobilization. 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.

D. *Digital 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.

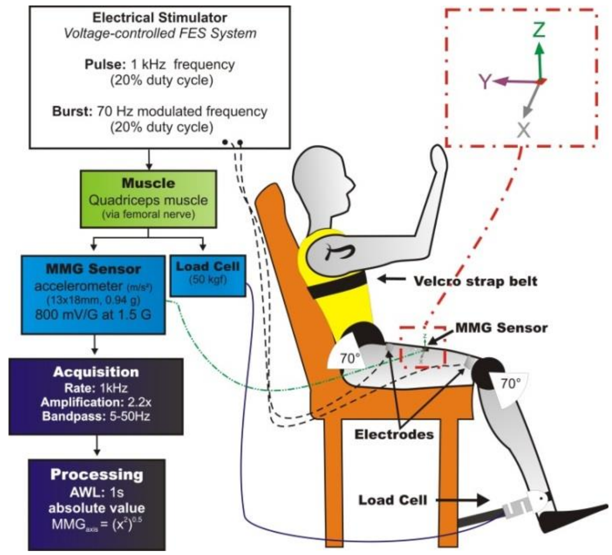

Figure. 2. Instrumentation layout and experimental set up.

Before the load cell attachment the FES-intensity was increased until the maximal electrically-evoked extension (MEEE) of knee joint. After the load cell placement, the FES-intensity required to reach the MEEE was applied and registered by load cell as force-100% to avoid any musculoskeletal injury. Ten-minutes rest interval was respected to avoid interference on fatigue protocol.

1) *Fatigue-protocol*

The fatigue-protocol was initiated without electrical stimulation along the initials 5s as illustrated in Fig. 3. FES-intensity was increased until and during the control to keep the force in force-100%. Instants were determined with the following rationale: Instant I, at the moment the manually controlled (by technician) stability of force-100% was reached to avoid the spurious signal from motion artifact; Instant II, when the FES-control was unable to keep force-100%; Instant III, slope down to force-65%, and Instant IV, slope down to force-30%.

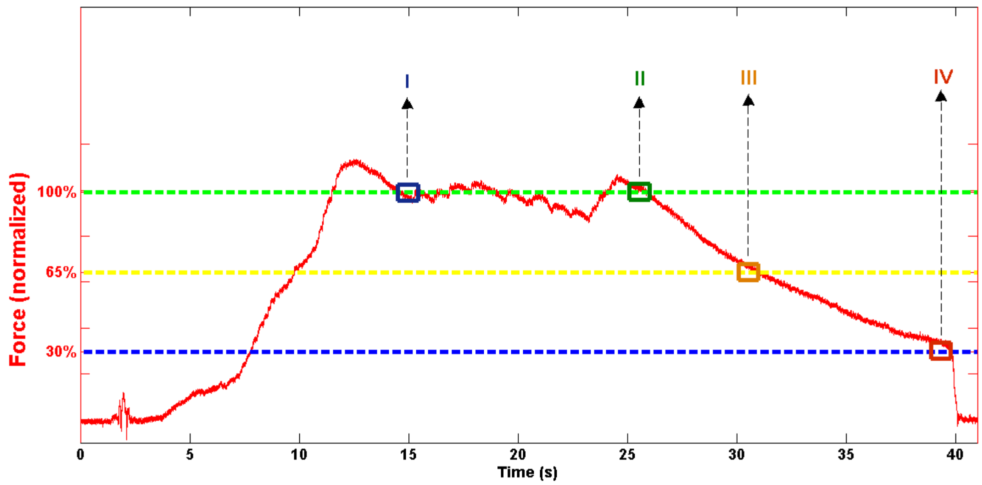

Figure. 3. Fatigue-protocol from one participant. Force: red line, 100%-force: dashed green line, 65%-force: dashed yellow line, 30%-force: dashed blue line. Rectangle blue: instant I, Rectangle green: instant II, Rectangle orange: instant III, Rectangle red: instant IV.

E. Data Processing

The signal was processed by custom-written MatLab® software version R2008a to X (transverse), Y (longitudinal) and Z (perpendicular) axes (to anatomical position). A third-order 5-50 Hz bandpass Butterworth filter was applied. The absolute value was extracted from MMG signal (x=|x|).

1) Noise attenuation

The average (to each MMG axis) from 1s during muscular silence (no FES or any movement) was defined as noise value. This noise value was reduced in all signals, and negative values (signal minus noise) were converted to 0 V (zero). The instant epochs (I to IV) duration was 1 s. Force was calibrated to initiate in 0 kgf (zero). To each axis, the data were normalized by the values of instant I.

2) Normalization process

The data were normalize by the point defined as unfatigued point (I) according the equation 1.

$$Energy\_NORM_{Axis\_ins} = \frac{\frac{1}{n}\sum_i^n \left|Energy_{Axis\_ins}\right|}{\frac{1}{n}\sum_i^n \left|Energy_{Axis\_I}\right|} \quad (1)$$

where, i is 1 and n is 1000 (sampling acquisition rate), *Axis* is the triaxial accelerometer axis and *ins* is the protocol instant (I-IV).

F. Statistical Analysis

The statistical analysis was tested with custom-written MatLab® software version R2008a. Because of the skew of the data, Friedmann test (related as non-parametric ANOVA) was computed to each axis (p value ≤ 0.05) in order to evaluate with the instants were different among them. Considering axes with statistical significance, for Post hoc analysis, Wilcoxon signed rank test was applied. The p value was corrected by Bonferroni adjustment for multiple comparisons; in this sense, differences were considered significant with $p \leq 0.0125$.

III. Results

The volunteers skinfold thickness was 19.1 ± 11.2 mm. The total time of fatigue-protocol (I-IV) was 31.74 ± 19.7 s. Table II shows the force and FES intensity values during the fatigue-protocol. The similar force values in instants I and II indicate that force control was achieved. The increase in FES magnitude with decrease in force corroborates the muscular fatigue.

TABLE II
Force and FES-Intensity

Instant	Force (kgf)	FES-Intensity (V)
I	7.3 ± 3.9	152 ± 38.2
II	7.2 ± 3.9	195.2 ± 45.5
III	4.6 ± 2.6	222.2 ± 39.8
IV	2.3 ± 1.2	236.5 ± 31.2

Fig. 3 shows the MMG energy response to all accelerometer axes in each instant. On these results, the X and Y-axes (transverse and longitudinal) showed statistical significance with an energy decrease. X-axis on the instants II and IV, with relation to instant I. Y-axis, on the final instant (IV) was staticsally lower than instants II and III. Z-axis presented the same decrease tendency that X and Y-axes; however, there is insufficient statistical power. Indeed, even at the same force values, instants I and II (Table II), the MMG X-axis energy (Fig. 3) showed a decrease, indicating muscular fatigue, because on the following instants (III and IV) the energy decline remains. This response do not occur with $p \leq 0.0125$ to Y and Z-axes.

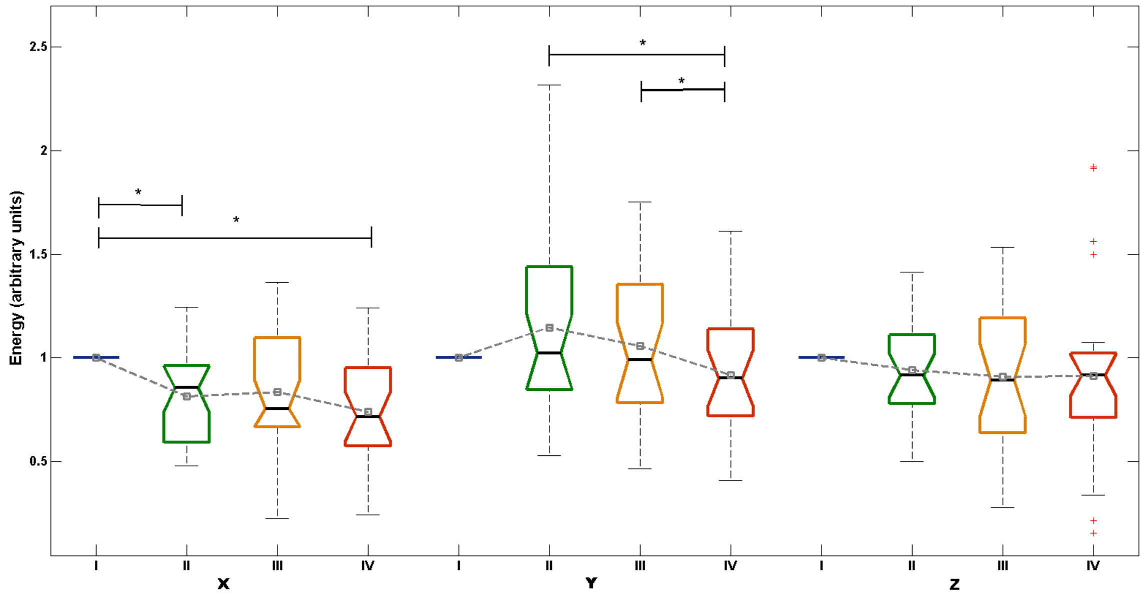

Figure. 3. MMG energy signal boxplot from fatigue-protocol electrically evoked in spinal cord injured participants. Instants: I (blue), II (green), III (orange), IV (red). +: outliers data. Gray Square and dashed line: mean value. *: $p \leq 0.0125$.

IV. Discussion

According to Bigland-Ritchie and Woods [4], muscular fatigue is any reduction in the force generating capacity of the total neuromuscular system regardless the force required in any given situation. In our results, the X and Y-axes (transverse and longitudinal) showed statistical significance with energy decrease. X-axis on the instants II and IV, with relation to instant I. Y-axis, the final instant (IV) was statiscally lower than instants II and III. The Z-axis presented the same decrease tendency that X and Y-axes; however, there is insufficient statistical power. Orizio et al. [5] concluded that at high levels of effort, MMG_{RMS} (temporal domain - RMS) feature decreases and the hypothesis may be the decrease in the recruitment of fast (glycolytic) fibers possibly due to muscular fatigue. MMG energy decline also was found for Faller et al. [6] that evaluated able-bodied participants in fatigue-protocol electrically evoked showed MMG_{RMS} decrease too. The MMG energy signal presented a decrease like force signal during fatigue as in our study. Paraplegic people reach muscular fatigue more rapidly than able-bodied people [7], but with the same MMG response tendency when muscle fatigue installs. The decrease in MMG energy possibly due to increases in the depolarization threshold, through Na^+ channels inactivation [8], which characterizes motoneuron adaptation [9] during prolonged FES application [10] that is an event that occurs during neuromuscular fatigue [11].

V. Conclusions

In the present work we investigated the response of triaxial MMG signals acquired from the quadriceps of spinal cord injured volunteers in a fatigue protocol. The MMG energy decreases over time with FES application. The MMG energy decreased due to neuromuscular fatigue in paraplegic subjects. X-axis between instant I (1 ± 0) and instant IV (0.74 ±0.27), and the same tendency was found to Y-axis between instant II (1.14 ± 0.44) and instant IV (0.91 ± 0.3).

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