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Correlation between Mechanomyography Features and Passive Movements in Healthy and Paraplegic Subjects

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Abstract—**Mechanomyography (MMG) measures both muscular contraction and stretching activities and can be used as feedback in the control of neuroprostheses with Functional Electrical Stimulation (FES). In this study we evaluated the correlation between MMG features and passive knee angular movement of *rectus femoris* and *vastus lateralis* muscles acquired from healthy volunteers (HV) and spinal cord injured volunteers (SCIV). Twelve HV and thirteen SCIV were submitted to passive and FES elicited knee extensions and in each extension, eleven windows of analysis with 0.5s length were inspected. Temporal (RMS and INT) and frequency (MF and μ3) features were extracted. Spearman correlation coefficients (ρ) were computed in order to check correlations between the features obtained from both MMG sensors. The correlation between MMG_{MF} and MMG temporal analysis (RMS and INT) to HV was classified as positive, moderate (ρ from 0.635 to 0.681) and high (ρ from 0.859 to 0.870), and weak (positive e negative) to SCIV. These results differ from those obtained in voluntary contraction or artificially evoked by functional electrical stimulation and may be relevant in applications with closed loop control systems.**

I. Introduction

TRIAXIAL accelerometers are used to assess corporal balance and to measure the lateral oscillation during muscular contraction (or stretching) [1, 2] in a technique defined as mechanomyography (MMG) [3]. MMG signals can be indicated as feedback in the control of myoelectrical prostheses [5, 6] or neuroprostheses with functional electrical stimulation (FES) [4], using temporal and spectral features [7, 8]. During FES applications, the electrical stimuli may provoke interference on electromyographic (EMG) signals due to circuitry limitations. MMG measures mechanical oscillations of muscles under contraction, it is not affected by electrical pulses yielded during FES application [9]. MMG sensors can be placed on antagonist muscles groups, and while agonist fibers contract, most antagonist fibers can be relaxing. As the MMG measures both muscular contraction and stretching [1, 2], it can be used to eliminate the irregular responses originated from movement artifacts in order to allow the development of closed loop control systems using MMG.

The study of such irregular responses can help discriminate passive movement irregular responses from active responses of muscular contractions. Therefore, the goal of this paper is to investigate and discuss the correlation between MMG features and passive knee angular movement of *rectus femoris* (RF) and *vastus lateralis* (VL) muscles in healthy volunteers (HV) and spinal cord injured volunteers (SCIV).

II. Methods

A. Subjects

This study was approved by Pontifícia Universidade Católica do Paraná's (PUCPR) Human Research Ethics Committee under register 2416/08. The volunteers involved in the research were twelve HV (N=12, 31.45±4.56 yo) and thirteen SCIV (N=13, 32.06±9.46 yo). The SCIV had injury in spinal cord levels ranging from C_5 to L_1, with complete or incomplete voluntary knee movement, and degrees 0 to 4 in Higuet Power scale (0 - 5) [10].

B. Measuring Apparatus

MMG sensors were positioned over the muscle belly of RF and VL muscles using double-sided adhesive tape. The sensor placed on RF was equidistant between the anterosuperior iliac spine and top of the patella and on the VL was equidistant between the greater trochanter and the lateral condyle of the femur. An electrogoniometer, placed laterally to the knee, acquired the range of movement as shown in Fig. 1.

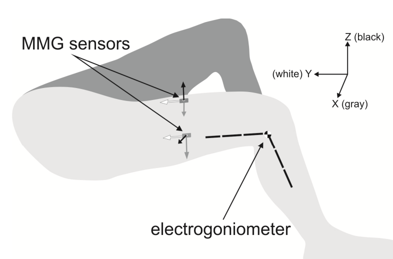

Fig. 1. Transducers placement and accelerometer axes orientation. Electrogoniometer fixed laterally to knee joint and mechanomyography sensors over the rectus femoris and vastus lateralis muscle bellies.

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C. MMG Sensor and Data Acquisition

The developed MMG instrumentation used Freescale MMA7260Q MEMS triaxial accelerometers with sensitivity equal to 800 mV/V at 1.5 G (G: gravitational acceleration). Electronic circuits allowed 10x amplification and 4-40Hz Butterworth third order filtering. A LabVIEW™ program was coded to acquire MMG signals. All signals and volunteers data were saved into European Data Format (EDF) files. The acquisition system contained a DT300 series Data Translation™ board working at 1kHz sampling rate. The modulus signal was computed from the three individual MMG sensor axes.

D. Research Design

The HV and SCIV volunteers were seated on an adapted chair with the hip and knee angles set to 70º [11] and 90º, respectively. The maximum knee extension angle was defined as 0º. The volunteers were advised to keep the body muscles completely relaxed during the protocol, thus avoiding the interference of movement artifact on MMG sensors. Three passive angular movements were elapsed by technicians with approximately $10º.s^{-1}$, starting with knee angle ranging from approximately 65º (leg flexed) to 10º (almost full leg extension). Eleven windows of analysis were extracted from the second passive angular movement. The peak of angular movement (lower knee angle value) was defined as the middle point and, then, five points were selected before and after the middle. The analysis window length (AWL) was 0.5s long. Each AWL was analyzed in time (root mean square – RMS, and Integral - INT) and spectral (median frequency - MF) domains, and μ3 [12], through which, uses the mean power frequency (MPF) to determine the skewness of the spectrum.

E. Data Presentation and Analysis

Knee angle data are presented in figures and MMG features data are presented in tables. Wilcoxon Signed Ranks Test was used between HV and SCIV in order to compare the speed of passive angular knee movement during the protocol.

Spearman correlation coefficients (ρ) were computed and investigated to check relations between the values of features obtained from both MMG sensors. Only results with statistical significance ($p<0.05$) are shown in Tables I and II.

III. Results

Room temperature was 25.25ºC ± 2.51ºC, and humidity was 62.66% ± 6.18% to HV whereas to SCIV, 20.61ºC ± 3.69ºC and 60.23% ± 4.49%, respectively. Temperature and humidity varied because the room has no temperature control system. The speed of passive angular knee movement during the protocol was different ($p = 0.033$) between HV ($11.29º±2.30º.s^{-1}$) and SCIV ($13.23º±2.72º.s^{-1}$). Figs. 2 and 3 show the knee angle values to HV and SCIV, respectively. Tables I and II show the ρ calculated to MMG features and knee angle.

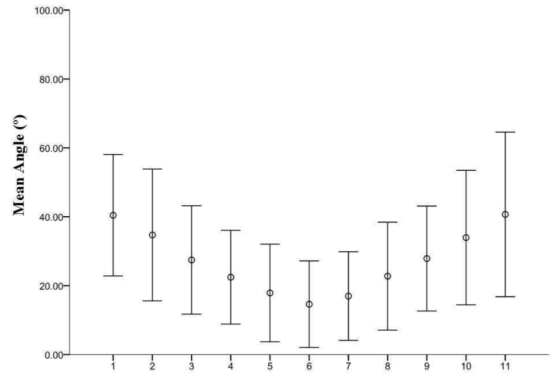

Fig. 2. Knee angle values of HV during passive movement. Abscissa: eleven selected windows of analysis. Analysis window length = 0.5s.

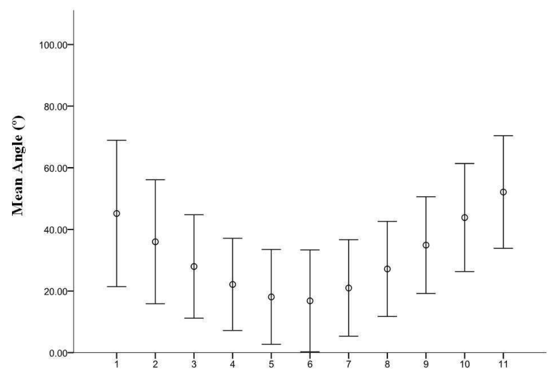

Fig. 3. Knee angle values of SCIV during passive movement. Abscissa: eleven selected windows of analysis. Analysis window length = 0.5s.

TABLE I

Spearman coefficients (ρ) between MMG features to HV (N=12)

Mus	Axis	Feature	Angle	MF	INT	RMS
RF	Z	μ3	-0.238^{**}	-0.871^{**}	-0.320^{**}	-0.277^{**}
	X	MF	0.17	1	0.290^{**}	0.251^{**}
		μ3	-0.207^{*}	-0.884^{**}	-0.318^{**}	-0.281^{**}
	Y	MF	0.200^{*}	1	0.342^{**}	0.293^{**}
		μ3	-0.225^{**}	-0.916^{**}	-0.364^{**}	-0.313^{**}
	Mod	MF	0.184^{*}	1	0.270^{**}	0.227^{**}
		μ3	-0.173^{*}	-0.027	-0.226^{**}	-0.244^{**}
VL	Z	MF	0.075	1	0.647^{**}	0.635^{**}
		μ3	-0.139	-0.892^{**}	-0.716^{**}	-0.702^{**}
	X	INT	0.281^{*}	0.106	1	0.955^{**}
		RMS	0.261	0.071	0.955^{*}	1
		μ3	-0.187^{*}	-0.811^{**}	-0.514^{**}	-0.485^{**}
	Y	MF	0.11	1	0.870^{**}	0.859^{**}
		μ3	-0.127	-0.887^{**}	-0.812^{**}	-0.802^{**}
	Mod	MF	0.122	1	0.681^{**}	0.669^{**}
		μ3	-0.231^{**}	-0.429^{**}	-0.496^{**}	-0.494^{**}

Mus= muscle, RF= *rectus femoris*, VL= *vastus lateralis*, p= significance level, r= correlation coefficient, HV= healthy volunteer, SCIV= spinal cord injured volunteer, MF= median frequency, RMS= root mean square, INT= integral, μ3= skewness of the spectrum, *= statistical significance $p < 0.05$, **= statistical significance $p < 0.01$.

TABLE II
SPEARMAN COEFFICIENTS (Ρ) BETWEEN MMG FEATURES TO SCIV (N=13)

Mus	Axis	Feature	Angle	MF	INT	RMS
RF	Z	MF	0.123	1	-0.168*	-0.174*
		μ3	-0.009	-0.302**	-0.681**	-0.687**
	X	MF	0.203*	1	-0.118	-0.12
		INT	-0.244**	-0.118	1	0.991**
		RMS	-0.246**	-0.12	0.991**	1
		μ3	-0.04	-0.346**	-0.657**	-0.655**
	Y	INT	-0.274**	-0.038	1	0.987**
		RMS	-0.257**	-0.017	0.987**	1
		μ3	0.144	-0.410**	-0.684**	-0.699**
	Mod	MF	0.244**	1	-0.138	-0.144
		INT	-0.228**	-0.138	1	0.992**
		RMS	-.201*	-0.144	0.992**	1
		μ3	0.08	-0.192*	-0.788**	-0.785**
VL	Z	MF	0.072	1	0.156	0.166*
		μ3	0	-0.426**	-0.813**	-0.822**
	X	MF	0.174*	1	-0.291**	-0.281**
		μ3	-0.275**	-0.071	-0.724**	-0.732**
	Y	MF	0.065	1	0.245**	0.234**
		μ3	-0.125	-0.530**	-0.780**	-0.780**
	Mod	μ3	-0.14	-0.026	-0.467**	-0.475**

Mus= muscle, RF= *rectus femoris*, VL= *vastus lateralis*, p= significance level, r= correlation coefficient, HV= healthy volunteer, SCIV= spinal cord injured volunteer, MF= median frequency, RMS= root mean square, INT= integral, μ3= skewness of the spectrum, *= statistical significance $p < 0.05$, **= statistical significance $p < 0.01$.

IV. DISCUSSION

According to Tables I and II, the correlation coefficient values of MMG features were different for HV and SCIV, which can be due to the incomplete relaxation of HV in quadriceps muscle, creating vibratory waves during passive movement, what is in accordance with Shinoara et al. [2]. Ebersole et al. [1] evaluated the response of MMG signal (RMS and/or INT) in HV and electromyography (EMG) during passive knee movement to VL muscle in different velocities (30, 90 and 150º.s^{-1}). The EMG magnitudes at each velocity were not different ($p > 0.05$) when compared to the values at rest. However, the MMG amplitude increased ($p < 0.05$) with enlargement in velocity. Ebersole et al. [1] hypothesized that the velocity-related increase in MMG amplitude, for the passive knee extension movements in VL activation, may have been associated with turbulences in intracellular and extracellular fluid mediums and/or cross-talk from the hamstring muscles. In this study, the knee angular velocity during passive movement was controlled by the technician, nevertheless the velocities between the HV (11.29º.s^{-1} ± 2.30º.s^{-1}) and SCIV (13.23º.s^{-1} ± 2.72º.s^{-1}) were different (Wilcoxon Signed Ranks Test showed $p = 0.033$). Regarding HV, Table I shows only one weak correlation ($p < 0.05$) between MMG amplitude (INT) and knee angle in X axis to VL muscle ($\rho = 0.281$). In Table II, regarding SCIV, weak negative correlations ($\rho < -0.30$) were found between INT (and RMS) to knee angle in X, Y and modulus of RF MMG sensor. The explanation for the positive correlation observed with HV and negative correlation to SCIV between MMG magnitude (INT) and knee angle can be due to the incomplete relaxation of quadriceps muscle in HV, creating vibrations/pressure waves during passive movement, what is in accordance with Shinohara et al. [2].

Considering HV data in Table I, the correlation values between MF and MMG amplitude (INT and RMS) were weak ($\rho < 0.30$) to RF muscle in X, Y and modulus. Conversely, to VL muscle of HV, the correlations were moderate (ρ from 0.635 to 0.681) and high (ρ from 0.859 to 0.870) to Z, Y and modulus axes. However, the SCIV presented weak positive and negative correlations to Z axis to RF muscle, and all axes to VL muscle. Thereby, HV showed only positive correlations during passive movement to MMG_{MF} and MMG temporal analysis (RMS and INT). This finding differs in voluntary contraction, according to Tarata [13], or FES application, according to Krueger-Beck et al. [14], due to MMG_{MF} and MMG_{RMS} being co-related with a negative coefficient.

The third-order central moment $MMG_{\mu 3}$ (that uses MPF to determine the skewness of the spectrum) [15], presented negative correlation with respect to MMG amplitude (INT and RMS) to all axes and their modulus to RF and VL muscles both in HV and SCIV. The negative correlations showed coefficient values from weak to high (ρ from -0.277 to -8.22). The presented correlation between $MMG_{\mu 3}$ and MMG_{MF} were negative to HV and SCIV. To HV, the negative correlations were present in all axes of RF muscle, and all axes and modulus to VL muscle. To SCIV there were negative correlations in all axes and modulus to RF muscle and to Z and Y axes to VL muscle. According to Madeleine et al. [12], during sustained fatiguing contractions, the MMG_{RMS} increases and $MMG_{\mu 3}$ decreases along the time, which can be compared to the results of negative correlations informed in Tables I and II to passive movement. However, for Madeleine et al. [12], MPF (correlated with MMG_{MF}) decreases during sustained fatiguing contractions too, what did not occur in this study because $MMG_{\mu 3}$ and MMG_{MF} are negatively correlated. According to the results of Madeleine et al. [12], the correlations should be positive; but this discrepancy may exist because our study was conducted with passive movements.

The correlations observed between $MMG_{\mu 3}$ and knee angle were negative. To HV and RF muscle, the correlations in all axes and their modulus were weak (ρ from -0.173 to -0.238), and to VL muscle, in X axis and axes modulus, they were also weak, ρ = -0.187 and ρ =-0.231, respectively. To SCIV only one weak negative correlation was found in X axis of VL muscle (ρ = -0.275). These results indicate that $MMG_{\mu 3}$ is affected by movement artifact. We found correlations between MMG_{MF} and knee angle in Y axis and axes modulus to RF muscle in HV, and in X axis and axes modulus to RF muscle and in X axis to VL muscle in SCIV. MMG_{MF} and knee angle presented positively weak correlations ($\rho \leq 0.203$) in all cases. Both $MMG_{\mu 3}$ and MMG_{MF} are spectral analysis features and they showed antagonist responses to knee angle during passive movements.

V. Conclusions

Temporal analyses of the knee angle did not show significant correlation between MMG_{INT} or to MMG_{RMS} to HV, and only two weak negative correlations were found to SCIV. The third-order central moment, $MMG_{\mu 3}$, presented negative correlations between MMG amplitude features (INT and RMS) in all axes and the resulting modulus to RF and VL muscles both in HV as SCIV. The correlations between knee angle and $MMG_{\mu 3}$ were negative and weak ($\rho \leq -0.275$). The correlations between knee angle and MMG_{MF} were positively weak correlations ($\rho \leq 0.203$) to both HV and SCIV. The main result found in this study is that the correlation values between MMG_{MF} and MMG temporal analysis (RMS and INT) were always positive, moderate (ρ from 0.635 to 0.681) and high (ρ from 0.859 to 0.870) for HV, and were weak (positive e negative) for SCIV which differs from voluntary contraction or artificially evoked by functional electrical stimulation. Possibly the difficulty of HV getting their muscles totally relaxed during passive movement, a fact that does not occur with SCIV due impairment/loss of voluntary contraction.

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