Convex Hull Area in Triaxial Mechanomyography during Functional Electrical Stimulation

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Abstract: This study employed the convex hull in the analysis of triaxial mechanomyography (MMG) to determine hull area variations along prolonged muscle contractions elicited by functional electrical stimulation (FES). Closed-loop FES systems may need real-time adjustments in control parameters. Such systems may need to process small sample sets. The convex hull area can be applied to small sample sets and it does not suffer with non-stationarities. The MMG sensor used a triaxial accelerometer and the acquired samples were projected onto all planes. The hull determined the smallest convex polygon surrounding all points and its area was computed. Four spinal cord injured volunteers participated in the experiment. The quadriceps femoral muscle was stimulated in order to cause a full knee extension. FES parameters: 1 kHz pulse frequency and a 20 Hz burst frequency. Adjustments in the stimuli amplitude were controlled by a technician to sustain the extension. The results showed that the convex hull area decreased over time. Since the polygons are related to MMG amplitude, decreasing areas were related to muscle fatigue. The convex hull area can be a candidate to follow muscle fatigue during FES-elicited contractions and analysis of short length epochs.

1 INTRODUCTION

Functional electrical stimulation (FES) allows the production of real muscle contractions that are artificially elicited by means of electric charges applied to paralyzed muscles (Bajd et al., 1981, Langlois et al., 2010). In addition to easing locomotion problems, the electrical current applied to a spinal cord injured subject brings physiological and biomechanical benefits to the subject's health (Peng et al., 2011).

During FES sessions, monitoring muscle response to the electrical stimuli is a way of investigating the evolution of muscle condition. Mechanomyography (MMG) is a technique that registers muscle vibrations and can help investigate mechanical and physiological properties of contracting muscles. Stokes and Cooper (1992) reported that MMG is related to force production whereas Petitjean et al. (1998) stated that evoked MMG amplitude is a good index of motor unit recruitment. MMG can also be used to observe muscle fatigue installation, as a force suppressor phenomenon, during FES programs performed in rehabilitation protocols (Gobbo et al., 2006). Triaxial MMG uses a 3D accelerometer that registers muscle vibration in three orthogonal directions simultaneously. It was already employed in the study of muscle fatigue installation or neuronal adaptation during FES (Nogueira-Neto et al., 2011), in which 1 s epochs of MMG signals were analyzed. However, in closed-loop control of FES systems using MMG parameters, updating the control strategy may require epochs less than 1 s long. Using such epochs, spectral (such as mean frequency and spectral kurtosis) and temporal parameters (like those that require constant signal variance) can be contaminated by non-stationarity effects and this becomes a problem for signal analysis and classification (Fong et al., 2011) because parameters have limited discriminatory power (Xie et al., 2009). So, it is necessary to investigate techniques that can also be applied to short epochs in neural control systems.

Triaxial MMG allows the projection of a single coordinate (defined by the values of each acceleration axes) onto three representational planes

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(XY – XZ – YZ). In the space defined by the vibratory axes, Graham's convex hull algorithm (Graham, 1972) can identify the smallest convex polygon that encloses all points in a plane. The scattered plot of the coordinates represents the spatial distribution of muscle vibrations. After determining such polygon, its area can be computed and it is closely related to the amplitude of MMG signals in these directions. The area computation is independent of the number of points (related to the triaxial MMG epoch duration) and, thus, non-stationarity issues do not limit the discriminatory power of signal descriptors. The validation of the convex hull area as signal analysis technique can provide a new method to investigate bi- or triaxial MMG during epochs less than 1s long during closed-loop FES.

As long as FES is continuously applied to paralyzed muscles, the installation of muscle fatigue and neuronal adaptation can change the muscle vibratory response (Jailani and Tokhi, 2012). Since no previous work was found using convex hull and bi- or triaxial MMG for muscle condition analysis during FES, we propose to investigate whether the convex hull area of planar finite MMG coordinates set can identify changes in muscle condition during knee maximum extension evoked by prolonged FES application.

2 METHODS

2.1 Volunteers

The data were obtained from four male spinal cord injured volunteers submitted to FES. The experiment was approved by the research ethics committee of Pontifícia Universidade Católica do Paraná (letter of approval 2416/08). Participants were instructed about the protocol and, after signing an informed consent term, trichotomy and skin cleaning were performed previous to the positioning of MMG sensor and FES electrodes. Figure 1 shows the experimental setup for the subjects, sensors and electrodes during the protocol.

2.2 Functional Electrical Stimulator

A multichannel functional electrical stimulator was used to excite the quadriceps femoral muscle. The FES waveform was a rectangular wave with pulse frequency of 1 kHz, because it is preferable so as to cause a forceful motor response (Ward and Robertson, 1998), and a 20 Hz, 6% duty cycle burst frequency. A low duty cycle allows efficient contractions with less undesired metabolic effects. A low burst frequency, preferably below 70 Hz, may postpone muscle fatigue installation and avoid tetanic contractions being 20 Hz the limit before reaching muscle fasciculation (Petrofsky, 2004). The stimulator worked in open-loop and a technician changed the stimuli amplitude as required.

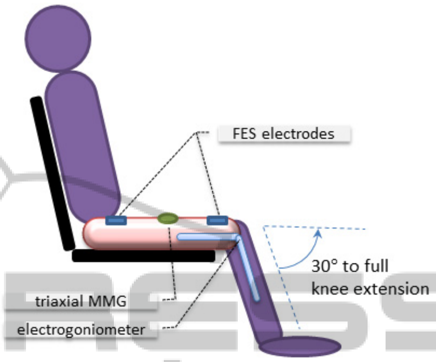

Figure 1: Experimental setup. FES elicited extension from 30° (rest) up to 0° (full extension). MMG sensor was placed over the quadriceps muscle belly. The electrogoniometer registered the angle of the knee. FES electrodes: over the femoral triangle and the suprapatellar region.

2.3 Acquisition System

The developed MMG instrumentation used a Freescale MMA7260Q MEMS triaxial accelerometer (13x18mm, 0.94 g, 800 mV/G sensitivity at 1.5 G [G, gravitational acceleration] – see Figure 2 for axis orientation). The electronic circuits allowed 10x amplification. A LabVIEW program was responsible for the acquisition, pre-conditioning and processing of all signals. The acquisition hardware was a commercial Data Translation DT300 board working on a sampling rate of 1 kHz. The conditioning phase prepared for analysis the first 30 s after the knee angle reached maximum extension.

2.4 Experimental Protocol

The participant's left lower limb was initially positioned at 30º of the maximum knee extension (0º). FES caused the knee to fully extend. The manual adjustments in FES amplitude performed by the technician sustained the extension between 3º e 0º.

2.5 Convex Hull Processing

Each ordinate pair $[(x1, y1); (x2, y2); \dots; (xN, yN)]$ represents a point in a plane. Figure 3 shows the dispersion of 1000 ordinate pairs of a triaxial MMG signal, but only for X and Y axes.

The hull was computed based in the algorithm proposed by Graham (1972) with small modifications. The routine determines the convex hull $FC(S)$ of an ordinate pairs set $S = [s0, s1, \dots, sN]$ in the plane, where N depends on the epoch length. At every 1 s epoch, a vector S was processed to find the external points that define $FC(S)$.

Basically, the process can be defined in three phases: (i) identify the point with the smallest ordinate, i. e., the pivot point; (ii) compute the angles of all other pairs in relation to the pivot, resulting in a vector of angles sorted in ascending order and (iii) use the cross product to determine the angle formed by two line segments defined at every consecutive three pairs. In the case of a negative cross product, the intermediate pair is discarded for it is an internal point.

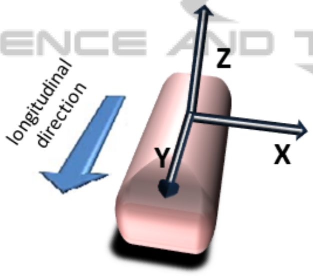

Figure 2: Orientation of MMG sensor's axes. Solid in red: perspective of the limb segment representing the thigh. Directions: Z – antero-posterior; X – lateral, and Y – longitudinal.

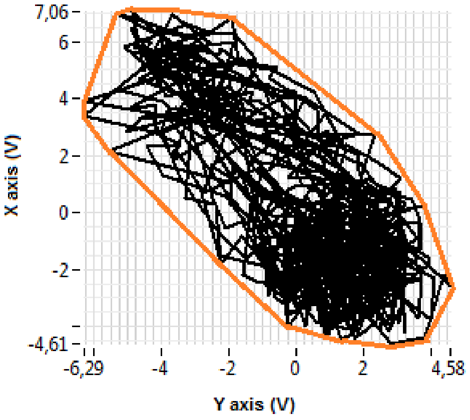

Figure 3: Dispersion of 1000 ordinate pairs from a 1 s triaxial MMG signal. Pairs were linked with black solid lines. The orange contour represents the convex hull.

The last phase is repeated successively and recurrently until no point in discarded from the current $FC(S)$. Finally, the routine determines the area of $FC(S)$.

2.6 Statistical Analysis

The area in each plane was normalized as a percent of mean area. Linear determination coefficients (R^2) were computed to investigate how much a regression line expresses the evolution of the area of FC(S) along the extension maintenance.

3 RESULTS

Figure 4 shows the convex hull area at every epoch. All curves presented a gradual decrease in the values of $FC(S)$. One can note that for some volunteer data (e.g., Patients A and C) there are variations in the trend of area values of different planes.

Table 1 shows the linear determination coefficients (R^2) for all curves. Data imply the existence of strong linear correlation in the trends, except for Patient C. All regressive line slopes were negative, evidencing a decline in the trend (–0.0171 to –0.069).

Table 1: Determination coefficients of regression lines.

Patient	XY	XZ	YZ
A	0.8404	0.9145	0.8831
B	0.9184	0.8245	0.9397
C	0.2642	0.324	0.6338
D	0.9605	0.9438	0.9527

4 DISCUSSION

The contracting muscle vibrates when sufficiently excited by FES, and the MMG captures the muscle lateral oscillation in three orthogonal directions. Each axes pair delimited a plane and Figure 4 shows that the area of $FC(S)$ presented a gradual reduction in all defined planes during the contraction.

Around the hull areas of Patient C, at instant 25 s, there is a transient in all planes. Incautious placement of sensors was avoided as well as the patients did not hit the leads during the experiment. A possible explanation would be that this event is a result of the recruitment of new motor units during the evoked task. The recruitment of motor units while applying FES can follow a non-obvious pattern of sequencing, depending on muscle fiber types (Gregory and Bickel, 2005). Therefore, the muscle of Patient C can be more responsive to variations in FES amplitude and this responsiveness lead to greater oscillations in the triaxial MMG axes. After the transient, however, the area of $FC(S)$ diminished again, revealing a decreasing trend in MMG amplitude but less pronounced in the XZ plane, the transversal plane. The observed overall decrease is consistent with the findings of other researchers. Progressive decreases in MMG amplitude were observed in fatiguing isometric contractions of the erector spinae muscle (Yoshitake et al., 2001). The integrated amplitude of rectus femoris MMG response also decreased with force production (Stokes and Dalton, 1991) that indicates that motor unit recruitment decreases with the installation of muscle fatigue and it could explain the reduction in the hull area.

The main motivation for using computational geometry was the possibility of employing analysis with short length epochs without non-stationarity problems. Its algorithm can be easily incorporated in microcontroller units employed in closed-loop FES systems with a low computational cost and capable of providing real time efficiency (Yun-Hui, 1999).

The use of epochs less than 1 s in length is not recommended for analysis of electromyographic (EMG) parameters (Beck et al., 2005), as well as for biomechanical data during dynamic contractions (Schwartz et al., 2012) due to stationarity issues. Wavelet analysis is a recommended technique to study non-stationary signals (Rioul and Vetterli, 1991). Alternative to the complex hull analysis is principal component analysis (PCA), an statistical method that explains the covariance of multivariate signals by means of a small set of components and is less susceptible to outliers (Hubert and Rousseeuw, 2005).

The relationship between eccentric and concentric muscle contractions was studied with decomposition of MMG and EMG signals in principal components (Qi et al., 2011). This work focused in convex hull because microcontroller-based closed-loop FES control systems need short response times and this implied the use of short length epochs what could eventually impair the results with PCA (Osborne and Costello, 2004). Nevertheless, PCA had been already used in real-time control systems (Chapin et al., 1999) and robust PCA algorithms may be computed really fast (Hubert and Rousseeuw, 2005).

The reduction in the hull area can occur due to the attenuation in the amplitude of MMG signals in any axis. Generally, a monoaxial sensor registers the signal in the muscle normal direction and does not acquire vibrations in other directions (Akataki et al., 1999). Therefore, triaxial accelerometry favors the investigation of what is happening in vibration planes.

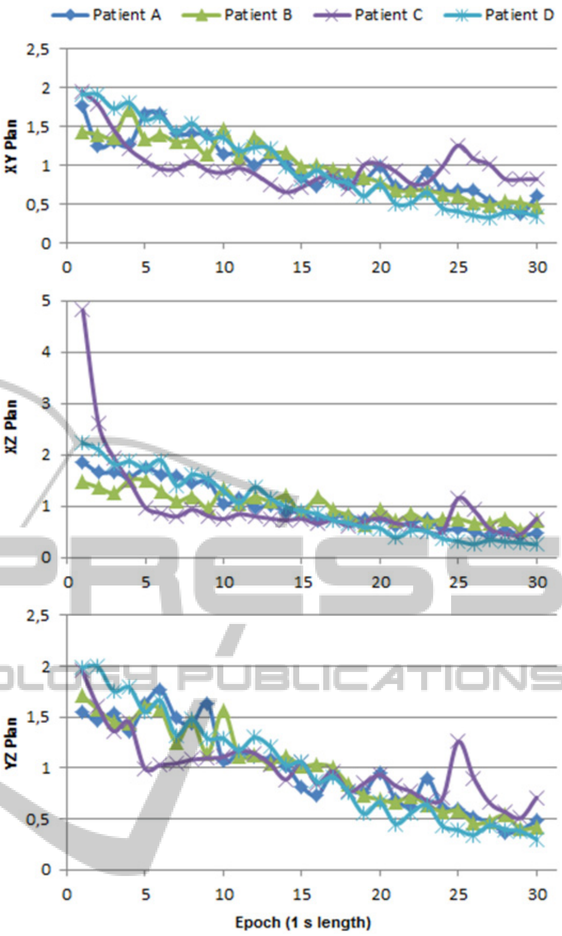

Figure 4: Convex hull area (in V^2) vs. epoch.

While a technique under study, data normalization is non-problematic, because absolute values can depend on volunteer, FES parameters and hardware/software amplification stages. A limitation of this technique is intrinsic to the method. The area enclosed by the hull does not represent the area of the polygon exactly defined by the pairs in the plane. However, the hull determination can be compromised if outliers are present in the samples. The number of subjects investigated was small because not all volunteers could hold an artificially sustained contraction for as long as 30 s.

Investigating MMG spectral parameters in voluntary isometric contractions, Tarata et al. (2001) observed a decrease in the MMG mean spectrum frequency for biceps and brachioradialis muscles. In studies previously published (Nogueira-Neto et al.,

2011) using FES and a spinal cord injured person, we have also found that the mean frequency decreases during the periods of extension maintenance. Therefore, the results presented in this paper are consistent with studies already published and show that this technique can be useful in following the evolution of FES-elicited muscle contraction. Convex hull area, despise its limitations, can be a promising candidate as a parameter indicating muscle fatigue in closed-loop FES control systems.

5 CONCLUSIONS

In this study, we proposed the use of a computational geometry technique known as the convex hull of a finite set of planar points in the analysis of triaxial mechanomyography signals. During an open chain contraction and maximum knee extension evoked by functional electrical stimulation, the convex hull showed that its area reduced in all planes in a space defined by the three axes of the mechanomyography sensor. This reduction in the convex hull area was related to a decrease in force production due to suppressive performance phenomena like muscle fatigue.

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