Dynamic Electromyography Evaluation of Spastic Hemiplegia Using a Linear Discriminator

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Abstract—Spastic hemiplegia (SH) is a type of cerebral palsy characterized by an uncontrolled increase of muscle tone on one side of the body. Superficial dynamic electromyography (SDEMG) signals, illustrate the contributions of the action potentials of motor units on the surface of muscle groups of the lower limbs during gait. This paper studies the SDEMG signals of patients with SH, acquired at the Gait Laboratory of the Hospital Ortopédico Infantil. Time and Frequency domain indicators were determined in order to evaluate the kinematics classification of SH from the electromyographic point of view. The applied indicators were: accumulated energy, non-linear accumulated energy, mean power frequency (MPF), spectral energy, bandwidth and wavelet decomposition. In order to identify the threshold and the error between each pair of types the following was used: one-way ANOVA with p value <0.05, a table of maximum error between each pair of types the following was used: α = 0.05 and Chernoff and Becker’s linear discriminator. Although it was not possible to discriminate between types I and III; a criteria was established that permits to differentiate among patients with SH (Type I, II or IV) with an error ≤1%.

Keywords—Dynamic Electromyography, Gait Analysis Wavelet Decomposition, Linear Discriminator, Spastic Hemiplegia.

I. INTRODUCTION

Spastic Hemiplegia (SH) is a type of cerebral palsy characterized by uncontrolled increase of muscle tone and reduced specific motor unit activation capacity of certain muscle groups on the upper and lower limbs of one side of the body. Surface dynamic electromyography (SDEMG) is a non-invasive technique for recording myoelectric signals related with motor unit group activation during the gait [1]. A rather complete study of pathological gait [2] can be obtained combining SDEMG signals, kinematics (angles), kinetics (momenta and power) and energy consumption. Classically, SH has been classified in 4 distinct types [3], based primarily on kinematics and in a minor grade on kinetics, and without considering de SDEMG at all. The SH types involve progressively the gait patterns of ankle, knee, pelvis, and hip; beginning with Type I (the least severe) and up to Type IV (the most severe). The muscle compromise is greater at bi-articular groups and on distal groups. The application of treatments based on such classification has improved the orthopedic surgery success rate [3], nevertheless the successful number of surgeries does not yet reach acceptable levels. An analysis of SDEMG signals of SH patients, based on kinematics classification, could reveal important information regarding the muscular behavior for different types of SH. We proposed spectral and energy studies for SDEMG signals during the gait cycle, of a group of SH patients from the Gait Laboratory, of the Hospital Ortopédico Infantil, database [4]; in order to evaluate the relevance of the muscle components within the SH classical classification.

II. METHODOLOGY

A group of 252 electromyograms (42 records with 6 muscle group electromyogram each) from 14 patients with Spastic Hemiplegia, selected from a SDEMG local database, “A Venezuelan Gait Analysis Database,” [4], were used for this study. The distribution of patients is based on the classic kinematics-based classification [3]: four (4) records of normal subjects, twelve (12) Type I, nine (9) Type II, nine (9) Type III and eight (8) Type IV.

The SDEMG signals were acquired using a portable electromyograph system MA200 (Motion Labs Inc.) and digitized at 12-bit resolution, 1.5 kHz sampling rate. Surface electrodes were applied on the following muscle groups: rectus femoris, medial hamstrings, gastrocnemius (biarticular muscle groups) and vastus lateralis, anterior tibialis and soleus (monoarticular muscle groups). The SDEMG signal was then segmented so it would be limited to a gait cycle on the affected side. The raw data was statistically normalized (SDEMGn), the normalizing criteria [5] chosen is based on the estimate of the mean and standard deviation of the minimum and maximum values of the SDEMG signals contained within the database.

A set of twenty-one (21) indicators were calculated in Time, Frequency and Time-Scale+Frequency domains [6]. From the Time-domain subset two energy indicators were calculated: the Accumulated Energy (AE) and the Accumulated Non-linear Energy (ANE) [8][9][10]. A preliminary step takes us to evaluate the instantaneous Energy (E[n]) as:

\[ E[n] = (x[n])^2 \]  \hspace{1cm} (1)

where:

\[ x[n] \] represents the SDEMG raw normalized SDEMGn.

The AE represents the discrete integral of the instantaneous energy E[n] in time, as expressed on
equation (2), on which the information of the average of the two following samples has been added.

\[
AE[n] = AE[n-1] + \left( \frac{E[n+1] + E[n+2]}{2} \right)
\]  

(2)

where:

\( AE[n] \) is the current sample of AE.

Then, a Non Linear Energy Operator (NE) can be calculated:

\[
NE[n] = x^2[n] - x[n-1] \cdot x[n+1]
\]  

(3)

where:

\( NE[n] \) is the current sample of the non linear energy operator.

The current sample of the accumulated non linear energy operator (ANE), is calculated by adding to the previous sample the information of the two following samples from the averaged non linear energy operator, just as is expressed on equation (4):

\[
ANE[n] = ANE[n-1] + \left( \frac{NE[n+1] + NE[n+2]}{2} \right)
\]  

(4)

For frequency-domain and Time-Scale+Frequency-domain subsets, a classic spectral analysis (FFT, PSD and energy) was applied to the raw signal and each of a set of wavelet decomposition components. Prior to that, the Mean Power Frequency (MPF) indicator is calculated. MPF is the measure of the centroid frequency, calculated as indicated in equation (5):

\[
MPF = \frac{\sum_{i=1}^{N} f[i] \cdot P[i]}{\sum_{i=1}^{N} P[i]}
\]  

(5)

where:

\( N \): number of the SDEMG samples.

\( P[i] \): i-th sample of the spectral power.

\( f[i] \): i-th sample of the frequency vector.

The Bandwidth indicator was obtained identifying the frequency at which at least fifty percent of the spectral energy is reached.

The wavelet decomposition can be achieved by first filtering the SDEMGn through a High-Pass filter with a Hamming window of 28 points and cut off frequency of 20 Hz. Then applying a 4-th order Daubechies Discrete Wavelet Transform (DWT) [11]. A six term decomposition was performed (k=6). The Inverse Discrete Wavelet Transform (IDWT) was calculated, that way the signal was reconstructed with only one reconstruction detail. This process was repeated for each detail (six) and the low-pass component also known as the seventh decomposition detail.

The time domain indicators obtained from the SDEMGn signal where AE and ANE. While in the Frequency domain we have: MPF, BW and spectral energy. Using the wavelet decomposition the MPF and spectral energy were calculated for each detail.

A statistical analysis using a one-way ANOVA (\( p \leq 0.05 \)), then, pair wise mean maximum significant difference tables (two-tails t-student \( p \leq 0.05 \)) and discriminant linear analysis, was performed over all the indicators.

The ANOVA allows us to determine the muscle-indicator combination that can differentiate at least one type of SH. The pair wise mean maximum significant difference tables allow us to identify indicators that discriminate between type-pairs of SH. The discriminant linear analysis technique being used has the purpose of quantifying the threshold between each type-pair, from which the mean and standard deviation of each group is needed. This research used the linear discriminator proposed by Chernoff and Becker [7]. Fig. 1 illustrates that the group of the left side of the threshold \( c \) (Type 0) has a lower average than the right side group (Type 1), i.e. \( m_0 \leq m_1 \). The threshold between type-pairs can be obtained using equation (6):

\[
c = m_0 + \Delta_0 = m_1 - \Delta_1
\]  

(6)

where:

\[
\Delta_0 = \frac{m_1 - m_0}{\sigma_0 + \sigma_1}
\]  

(7)

\[
\Delta_1 = \frac{\sigma_1}{\sigma_0} \cdot \Delta_0
\]  

(8)

\( m_0 \): mean of Type 0 group

\( \sigma_0 \): standard deviation of Type 0 group

\( m_1 \): mean of Type 1 group

\( \sigma_1 \): standard deviation of Type 1 group

![Fig. 1. Threshold between two groups.](image)
threshold for normal population, with the estimated means and variances), respecting the conditions established previously by the procedure of analysis of variance and pair wise mean maximum significant differences tables procedures. For the result analysis the conditions with error that is \( \leq 10\% \) is chosen. The empirical error for the constructed algorithms must be carefully interpreted since it would be necessary to evaluate them with new data.

This statistical method allows us to evaluate the obtained results, comparing the initial classification of the patients with SH with the results achieved by the discriminant linear analysis in accordance with the previously established criteria for this analysis.

Finally, a best classifying combination(s) of indicators is encountered. Such combinations are those that have less than a 10% discriminating error when the classification criterion is only the SDEMG.

III. RESULTS

A. Mean and Standard Deviation of the indicators

The following tables present the mean and standard deviation of each one of the indicators calculated, for both Time and Frequency domain. The results for the Frequency domain indicators \( \text{AE} \) and \( \text{ANE} \) can be seen on Table I. Table II and III show the results for the Frequency domain applied to the raw signal and each decomposition detail of the respective wavelet.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>MEAN AND STANDARD DEVIATION OF AE AND ANE</th>
<th>( (\mu \pm \sigma) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE [p.u]</td>
<td>8.5705 ± 10.9265</td>
<td></td>
</tr>
<tr>
<td>ANE [p.u]</td>
<td>3.8215 ± 4.2302</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>MEAN AND STANDARD DEVIATION APPLYING FFT AND PSD</th>
<th>( (\mu \pm \sigma) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>BW [Hz]</td>
<td>70.8651 ± 34.3222</td>
<td></td>
</tr>
<tr>
<td>MPF [Hz]</td>
<td>186.7976 ± 69.1692</td>
<td></td>
</tr>
<tr>
<td>E [p.u]</td>
<td>3.7032 ± 6.6229</td>
<td></td>
</tr>
</tbody>
</table>

Based on the ANOVA, pair wise mean maximum significant difference tables and discriminant linear analysis, the following algorithm is proposed (Fig. 2)

![Algorithm](algorithm.png)

Fig. 2. Algorithm with error \( \leq 1\% \) without restriction to identify normal patients.

<table>
<thead>
<tr>
<th>TABLE III</th>
<th>MEAN AND STANDARD DEVIATION OF MPF AND ENERGY FOR EACH DETAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detail</td>
<td>MPF ((\mu \pm \sigma)) [Hz]</td>
</tr>
<tr>
<td>F</td>
<td>267.4529 ± 88.0581</td>
</tr>
<tr>
<td>1</td>
<td>506.7921 ± 6.6229</td>
</tr>
<tr>
<td>2</td>
<td>268.8054 ± 38.4472</td>
</tr>
<tr>
<td>3</td>
<td>159.3260 ± 24.0939</td>
</tr>
<tr>
<td>4</td>
<td>90.5492 ± 11.6672</td>
</tr>
<tr>
<td>5</td>
<td>44.9868 ± 6.8430</td>
</tr>
<tr>
<td>6</td>
<td>20.8613 ± 4.3691</td>
</tr>
<tr>
<td>LP</td>
<td>8.8346 ± 3.0188</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE IV</th>
<th>CONDITIONS FOR CLASSIFICATION OF SH WITH ERROR LESS THAN 1%, WITHOUT NORMAL PATIENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cond.</td>
<td>Muscle Group</td>
</tr>
<tr>
<td>A</td>
<td>MH</td>
</tr>
<tr>
<td>B</td>
<td>MH</td>
</tr>
<tr>
<td>B</td>
<td>VL</td>
</tr>
<tr>
<td>B</td>
<td>AT</td>
</tr>
<tr>
<td>B</td>
<td>G</td>
</tr>
</tbody>
</table>
IV. DISCUSSION

The results shown on Tables I, II and III allowed us to compare the orders of magnitude of the indicators, of both Time and Frequency domain. The frequency at which the MPF is found, is greater than the bandwidth BW. The significant frequencies of the signal range between 80 Hz and 500 Hz approximately. All the indicators obtained from the vastus lateralis muscle group allow us to discriminate at least one of the SH types, this tells us that the compensatory mechanism of the pathological gait should be studied.

Fig. 2 showed the proposed algorithm for evaluating the SDEM from SH patients. The threshold conditions for each muscle indicator combination have been discriminated between Type I, II and IV. It was not possible to differentiate between Type I and III patients. In order to perform the classification, the threshold condition of the indicators in the muscle groups that are observed in Table IV, is evaluated. If the condition is satisfied, then the patient is Type A, else the patient is Type B. It is necessary to evaluate all muscle indicator combinations, and the final patient classification decision must be made by simple majority.

V. CONCLUSION

Chernoff and Becker’s linear discriminators provide the necessary indicators that allow classifying SH patients, considering only superficial dynamic electromyography signals.

The proposed classification algorithm establishes the threshold conditions that are necessary to be verified, in order to differentiate between each SH type-pair combination. The classification algorithm was based on indicators with 1% or less error discriminating capacity between each type-pair, and restricted to the training pool for Hemiplegia patients only. Applying the algorithm among all the SDEM signals obtained an empirical error less or equal to 10%.

The best muscle group discriminators are: medial hamstrings, vastus lateralis, anterior tibialis and gastrocnemius. The MPF indicator calculated from the signal spectrum (raw and wavelet details 1, 2 y 4) allows discriminating between the SH I, II and IV types. However it was not possible to discriminate between type I and type III, from an electromyographic point of view, due to the scarce numbers of SDEM signals for type III within the studied database.

ACKNOWLEDGMENT

Special thanks to the Laboratorio de Marcha of the Hospital Ortopédtico Infantil and to the Grupo de Bioingeniería y Biofísica Aplicada of the Universidad Simón Bolívar.

REFERENCES