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Frequency analysis of lower extremity electromyography signals for the quantitative diagnosis of dystonia

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Abstract

The purpose of this study was to develop an objective, quantitative tool for the diagnosis of lower extremity dystonia. Frequency domain analysis was performed on surface and fine-wire electromyography (EMG) signals collected from the lower extremity musculature of ten patients with suspected dystonia while performing walking trials at self-selected speeds. The median power frequency (MdpF) and percentage of total power contained in the low frequency range (%AUC_{Total}) were determined for each muscle studied. Muscles exhibiting clinical signs of dystonia were found to have a shift of the MdpF to lower frequencies and a simultaneous increase in the %AUC_{Total}. A threshold frequency of 70 Hz identified dystonic muscles with 73% sensitivity and 63% specificity. These results indicate that frequency analysis can accurately distinguish dystonic from non-dystonic muscles.

Keywords

dystonia; frequency analysis; electromyography; lower extremity; electromyography

INTRODUCTION

Dystonia is a neurologic movement disorder typified by repetitive gestures or abnormal positioning of involved body parts due to sustained involuntary muscle contractions (Berardelli et al., 1998, Pont-Sunyer et al., 2010). The onset of symptoms is usually associated with or exacerbated by voluntary actions, and prolonged dystonic postures may constrain normal motions; affected individuals may even slow their movements in an attempt to suppress the dystonic drive (Sanger et al., 2010, Sanger et al., 2003).

Given the debilitating impact that dystonia may have on an affected individual's quality of life, accurate diagnosis and identification of involved muscles is paramount for effective management and treatment. However, currently no diagnostic tools allow for the objective and definitive diagnosis of the disease. Although studies utilizing positron emission

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest.

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tomography (PET) and magnetic resonance imaging (MRI) (Albanese et al., 2006) suggest a correlation between dystonia and the presence of lesions in the thalamus or the basal ganglia, the lack of consistent findings across all forms of dystonia has limited their utility (Albanese, Barnes, 2006, Brin M. F., 2004). As such, the diagnosis of dystonia is made purely on clinical assessment and is subject to the examining clinician's experience and ability to differentiate the symptoms of dystonia from other movement disorders (Lalli and Albanese, 2010).

Electromyography (EMG) is a technique used to measure the electrical activity produced by skeletal muscles that results in contraction. Dystonia is thought to be associated with distinct EMG patterns in the time-domain, including co-contraction of antagonist muscles, continuous EMG activity, multi-phasic (oscillatory) activation patterns, and antiphasic activity due to overflow of electrical activity to surrounding or uninvolved muscles (Berardelli, Rothwell, 1998, Marsden, 1984). Recent efforts to develop diagnostic tools for dystonia have shifted the focus from time-domain analyses to frequency-domain analyses of EMG signals. Frequency analysis of an EMG signal allows for the decomposition of the signal into its frequency components. Previous studies describe a low-frequency (< 30 Hz) drive to co-contraction in muscle pairs in primary forms of cervical (Tijssen et al., 2000) and limb dystonia (Farmer et al., 1998, Grosse et al., 2004). However, the presence of co-contraction is not a specific marker for dystonia (Carolan and Cafarelli, 1992, Malfait and Sanger, 2007) and hinges on proper identification of involved muscle pairs; thus, these results, although promising, must be interpreted with caution.

Due to the variability in the clinical and electrophysiological presentation of individuals affected by dystonia, we believe that diagnosis may not be made purely on the presence of co-activation. Instead, we propose that analysis of muscle activity *independent* of the activity of surrounding or antagonist muscles will provide significantly more valuable information that, when used in conjunction with overall clinical assessment, would allow for definitive diagnosis of dystonia. Thus, the purpose of this study was to develop an objective frequency domain-based method that would allow for the identification and diagnosis of dystonia in lower extremity muscles. We hypothesized that the previously described low-frequency drive would manifest in lower limb dystonia and that frequency domain analysis of EMG signals collected from affected muscles would demonstrate a spectral shift to lower frequencies.

METHODS

Ten patients (mean $\pm$ SD: 24 $\pm$ 18 years, 59 $\pm$ 25 kg, 1.61 $\pm$ 0.16 m, 22 $\pm$ 8 kg/m², 1 M/9 F) with suspected primary lower extremity dystonia were selected for this study. A retrospective analysis was performed on EMG recordings collected from the lower extremity musculature during clinical evaluation of their gait (Motion Analysis Laboratory, Mayo Clinic, Rochester, MN).

Lower extremity EMG recordings

Electromyography signals from 121 lower extremity muscles (3 to 10 muscles per leg) were collected while subjects performed three walking trials at self-selected speeds, with the option to rest between each trial. Each trial was completed prior to the onset of subjective fatigue. Fatigue was not reported by the patient or assessed by the physical therapist conducting the gait study. Furthermore, each walking trial involved submaximal contractions of the lower extremity musculature and was completed within 5 $\pm$ 2 seconds, which is well below the reported endurance time for the ankle and knee at all intensity levels (Frey Law and Avin, 2010). Muscles studied included the extensor digitorum longus (EDL), gastrocnemius (GC), gluteus maximus (GX) and medius (GD), hamstrings (HS), medial and

lateral hamstrings (MHS and LHS), iliopsoas (IL), lumbar paraspinals (LP), peroneus longus (PL), rectus femoris (RF), tibialis anterior (TA), and tibialis posterior (TP).

Bipolar stainless steel surface electrodes (12 mm disks; Motion Lab Systems, Baton Rouge, LA) were used to measure activity from the GC, GX, GD, HS, MHS, LHS, LP, RF, TA, and TP muscles. Inter-electrode distance was 18 mm with a 12×3 mm reference electrode bar between the sensors. All surface electrodes were connected to a differential input preamplifier with a high common mode rejection ratio (> 100 dB), input impedance (> 100 M Ω) and a base gain of 20 (Motion Lab Systems). Skin in the area where the electrode was placed was prepared by shaving if necessary and mildly abraded in accordance with the International Society of Electrophysiology and Kinesiology (ISEK) and SENIAM standards (Hermens et al., 2000). Electrodes were placed over the target muscle belly, parallel with the muscles fibers, and secured with Tegaderm (3M Health Care, Neuss, Germany). Target muscle electrode placement was confirmed by having each subject perform a voluntary contraction of the target muscle while verifying that EMG signal was present in that channel. Each subject also performed voluntary contractions of muscles which could contribute to crosstalk in the target channel (adjacent, antagonist, or agonist muscles) while confirming that EMG signal was not present in the channel for the target muscle.

Paired, fine-wire indwelling electrodes (nylon insulated stainless steel, 2 mm exposed tip, 25 gauge hypodermic needle; Motion Lab Systems) were used to measure activity from the EDL, IL, and PL muscles. All fine-wire electrodes were connected to a differential input preamplifier with a high common mode rejection ratio (> 100 dB), input impedance (> 100 M Ω) and a base gain of 20 (Motion Lab Systems). Skin in the area where the electrode was inserted was sterilized with alcohol in accordance with ISEK standards. Electrodes were inserted under ultrasound guidance with respect to anatomical landmarks as described in literature (Perotto and Delagi, 1994) and secured with Tegaderm (3M Health Care). Target muscle electrode placement was confirmed by electrical stimulation with a peripheral nerve stimulator (Neuro Technology, Kerrville, TX). The current (200 μ s, 1 Hz, square wave monophasic pulses) was increased to a level which created a minimal muscle contraction in the target muscle, and it was visually verified that the twitch only occurred in the target muscle.

Surface and fine-wire EMG signals were acquired at 2400 Hz per channel with an MA300 electromyography system (Motion Lab Systems) and digitized at 2400 Hz (PCI-6071e A/D card; National Instruments, Austin, TX). It has been reported in literature that the bandwidth of usable energy for surface and fine-wire EMG signals is between 20–500 Hz and 20–1000 Hz, respectively (Basmajian and De Luca, 1985). As such, the sampling rate is in accordance with the Nyquist theorem, which states that the sampling rate must be greater than twice the highest frequency component of the analog signal.

Frequency domain analysis

Frequency analysis was performed on raw EMG signals collected with both surface and fine-wire electrodes with a custom Matlab software program (MathWorks, Natick, MA). Raw EMG signals from individual muscles were detrended and filtered with a 10th order infinite impulse response notching comb filter (1.5 Hz bandwidth) to remove background instrumentation noise (60 Hz) and its harmonics. The signals were then transformed into the frequency domain using an n -point discrete fast Fourier transform (DFT). The number of points, n , used to calculate the DFT was determined by the next power-of-two from the number of data points in the raw EMG signal. The power spectral density (PSD) for each muscle was estimated using Welch's periodogram method with 50% overlap between segments and 1 Hz frequency resolution; segments were windowed with a rectangular window. Each PSD was then normalized to the maximum power value in each spectrum.

Quantification of spectral shift: MdPF and %AUC_{Total} calculations

Spectral shift was quantified by two parameters: the median power frequency (MdPF) and the percentage of the total power contained in the low frequency range (%AUC_{Total}). The MdPF describes the relative proportion of low and high frequencies in the spectrum. Thus, a left-shift of the MdPF to a lower frequency indicates a greater proportion of muscle fibers firing at a low frequency. Mathematically, the MdPF is the point that divides the spectrum into regions containing equivalent power, and was calculated for each trial using Equation 1 (Stulen and DeLuca, 1981) and averaged across the three trials for each muscle:

$$\sum_0^{MdPF} PSD(f) = \sum_{MdPF}^{\infty} PSD(f) = \frac{1}{2} \sum_0^{\infty} PSD(f) \quad \text{Eq. 1}$$

The total power contained within each spectrum was found by calculating the area under the PSD curve (AUC_{Total}) from 0 to 500 Hz. Although it has been reported that the usable energy within an EMG signal collected with fine-wire electrodes is in the 20–1000 Hz range (Basmajian and De Luca, 1985), visual inspection of the power spectra constructed from both surface and fine-wire EMG data showed minimal power above 500 Hz. The %AUC_{Total} was calculated according to Eq. 2:

$$\%AUC_{Total} = \frac{AUC_{Low}}{AUC_{Total}} = \frac{\sum_{10}^t PSD(f)}{\sum_0^{500} PSD(f)} \quad \text{Eq. 2}$$

where AUC_{Low} is the power contained in the range from 10 Hz to the upper threshold, t . The upper threshold was selected after two iterations. Initially, a value of 50 Hz was arbitrarily selected for preliminary analysis; subsequently, analysis of the receiver operating characteristic curve, as outlined in the next section, showed that an upper threshold of 70 Hz optimized the diagnostic performance of our method.

Clinical identification of dystonic muscles

The gold standard for the diagnosis of dystonia was the clinical assessment of each subject performed by a physical therapist (KCW) with 33 years of experience. In addition to obtaining a detailed family history, medical history, and physical examination, gait assessment and evaluation of the dynamic EMG tracings were also utilized to make the diagnosis. Four specific patterns in the dynamic EMG tracings were considered highly suggestive of dystonia: antiphasic activity, co-activation of antagonist muscles, nearly continuous activation, and oscillatory activity (Berardelli, Rothwell, 1998, Marsden, 1984).

Evaluation of each subject was performed twice: once immediately upon completion of the clinical gait evaluation, and a second time at least one month after the initial assessment was completed. Only muscles that were found to exhibit clinical signs of dystonia during both assessments were considered dystonic in our subsequent analysis.

Quantitative identification of dystonic muscles

Quantitative identification of dystonic muscles was achieved by selecting a cut-off MdPF, where muscles with an MdPF below this threshold would be classified as dystonic. The threshold frequency was selected by constructing a receiver operating characteristic (ROC) curve for five putative threshold median power frequencies: 40, 50, 60, 70, and 80 Hz. The mean MdPF values for the muscles studied were pooled and the sensitivity (s_n) and specificity (s_p) associated with each cut-off value was calculated. As noted previously, the gold standard for diagnosis against which the objective criteria was evaluated was the

clinical evaluation by a physical therapist with over 30 years of experience. The optimal threshold MdPF that maximized performance was determined by the Youden index (J) (Perkins and Schisterman, 2006), which is the vertical distance between the point on the ROC curve associated with a specific threshold value, and the ROC curve associated with random chance – a diagonal line from (0, 0) to (1, 1). The most favorable threshold MdPF is associated with the largest J. Equation 3 was used to calculate J; this equation assumes that s_n and s_p are equally weighted and does not take cost of misdiagnosis and disease prevalence into consideration.

$$J = s_n + s_p - 1 \quad \text{Eq. 3}$$

Variability in calculation of MdPF and %AUC_{Total}

To determine the amount of variability in the calculation of the MdPF and %AUC_{Total}, the standard deviation (SD) from the mean MdPF and mean %AUC_{Total} of the right and left RF, TA, GC, and PL muscles from each subject was calculated (subjects 4 and 5 did not have data for the right and left RF muscle). Variability was assessed with box-plots of the SDs from the mean MdPF and mean %AUC_{Total}

RESULTS

Subjects

Subject characteristics (gender, age, height, clinical diagnosis) are summarized in Table 1. Of the 121 lower extremity muscles studied, 37 muscles exhibited clinical signs of dystonia. Figure 1A shows a representative raw EMG signal collected during a single trial from one subject, as well as the PSDs for a normal non-dystonic right peroneus longus muscle (Figure 1B) and for a dystonic right peroneus longus muscle (Figure 1C).

Quantitative identification of dystonia

The ROC analysis (Table 2 and Figure 2) showed that the threshold MdPF of 70 Hz was associated with the largest value for the Youden index ($J = 0.40$), and, therefore, optimized the sensitivity ($s_n = 0.73$) and specificity ($s_p = 0.67$) of our method. This value was subsequently used for the calculation of %AUC_{Total} and as an upper cut-off value for the classification of muscles as dystonic or non-dystonic. Fifty-five muscles had an MdPF lower than the threshold value of 70 Hz and were identified by our objective method as dystonic.

Results from the spectral analysis performed on the surface and fine-wire EMG data collected during the walking trials from a single representative subject are shown in Figure 3. Clinical assessment of this subject indicated that the R RF, R HS, L IL, R IL, L LP, R LP muscles exhibited dystonic behavior. Quantitative assessment indicated that all six muscles had an MdPF lower than the predetermined 70 Hz threshold (Figure 3A). Furthermore, individual and averaged results for %AUC_{Total} showed that muscles with a mean MdPF < 70 Hz were found to have a %AUC_{Total} > 50% (Figure 3B). In contrast, muscles with a mean MdPF > 70 Hz were found to have a mean %AUC_{Total} of approximately 30%.

Trial-to-trial measurement variability

Assessment of the standard deviations from the mean MdPF and mean %AUC_{Total} showed minimal variability between trials (Figure 4). On average, the median standard deviation from the mean MdPF was less than 10 Hz (Figure 4A). The median standard deviation from the mean %AUC_{Total} was less than 10% (Figure 4B). Although several outliers were present, the data, except for the MdPF of the LPL and RPL, are relatively invariant. Thus,

the mean MdPF and mean %AUC_{Total} values were representative of the individual trials and were used for the analyses presented in this paper.

DISCUSSION

The present study marks the first time that spectral analysis of EMG signals has been utilized for the diagnosis of dystonia. The results presented in this paper show that muscles exhibiting dystonic behavior have a characteristic shift of their power spectra to lower frequencies, resulting in an MdPF of less than 70 Hz. This threshold MdPF of 70 Hz could detect dystonia with 73% sensitivity and 67% specificity. Furthermore, a shift in the MdPF to lower frequencies resulted in a concomitant increase in the proportion of the total power contained in the low frequency range (%AUC_{Total}).

Our findings suggest that identification of dystonic muscles may be made independent of the electrical activity found in other muscles. This is in contrast to previous investigations, which identified patterns of co-contraction in the splenius/sternocleidomastoid muscles in primary forms of cervical dystonia (Tijssen, Marsden, 2000), and the tibialis anterior/gastrocnemius and extensor/flexor digitorum longi muscles in limb dystonia (Farmer, Sheean, 1998, Grosse, Edwards, 2004). However, utilization of co-contraction as a marker for dystonia has several limitations. For one, it is dependent on correctly identifying and measuring the activity from involved muscles. The above studies constrained their analyses to a single pair of muscles and may have precluded involved muscles from the analyses. Furthermore, co-contraction has been observed in normal muscles performing isometric contractions (Carolan and Cafarelli, 1992), and levels of co-contraction were actually found to be decreased in muscles of individuals affected by upper extremity dystonia compared with normal healthy controls (Malfait and Sanger, 2007). Thus, the sensitivity of co-contraction for the diagnosis of dystonia is severely limited.

One limitation of this study is the lack of an accepted objective gold standard against which the diagnostic accuracy of our method was assessed. Future studies would involve additional measures to ensure the accuracy of clinical diagnosis, such as assessment by multiple individuals specializing in gait disorders. Additionally, there is a lack of normative data for spectral parameters associated with specific lower extremity muscles. The distribution of power in the frequency spectrum is dependent on the relative proportion of fast and slow-twitch fibers present in the muscle, and thus, different muscles will have different spectral distributions. Further research in this area requires collection of EMG signals from normal subjects to characterize the spectral distribution of normal muscles; this would allow for comparison on a muscle-by-muscle basis. Finally, the method employed to perform the frequency analysis assumed that the EMG signals were stationary and would have frequency spectra that were constant over time. This assumption does not necessarily hold in our analyses since the EMG signals were collected as subjects were walking. Rather, the signals are cyclostationary and future work should utilize instantaneous time-frequency analysis of the signals to give a more meaningful description of muscular electrical activity.

CONCLUSION

Frequency domain-based analysis of surface EMG signals collected from the lower extremities during gait provides a quantitative measure of dystonic behavior in muscles. Muscles exhibiting clinical signs of dystonia were found to have a shift in their power spectral distribution, resulting in a decreased value for the MdPF and concomitant increase in the value for the %AUC_{Total}. A threshold frequency of 70 Hz identified dystonic muscles. These results indicate that spectral analyses of surface EMG signals may be a valuable

clinical tool that can aid physicians in the detection, diagnosis, and clinical decision-making for individuals affected by dystonia.

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Biographies

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Figure 1.

Results from frequency domain analysis of lower extremity surface and fine-wire electromyography (EMG) signals. A) Representative raw EMG signal collected during a single trial from one patient, B) power spectral density (PSD) of a non-dystonic right peroneus longus muscle, and C) PSD of a dystonic right peroneus longus muscle. The shaded regions in B) and C) span the 10 to 70 Hz bandwidth used to calculate the percentage of total power contained within the low frequency bandwidth of interest (%AUC_{Total}); the median power frequency (MdPF) of the spectra in B) and C) is indicated by the dashed vertical line. The dystonic muscle has a shift in its MdPF to a frequency that is less than 70 Hz.

Figure 2.

Receiver operating characteristic (ROC) curve demonstrating the diagnostic performance for different threshold frequencies. Sensitivity (true positive rate) is plotted on the y-axis, and 1-specificity (false positive rate) is plotted on the x-axis. The diagonal dashed line from (0, 0) to (1, 1) is the ROC curve due to random chance. The optimal threshold frequency occurs at 70 Hz ($J = 0.40$) and is indicated by the asterisk (*).

Figure 3.

Results from three walking trials from a single, representative subject. A) Median power frequency (MdPF), B) Percentage of total power contained within the low frequency bandwidth of interest (%AUC_{Total}). The objective criteria (MdPF = 70 Hz, dashed horizontal line in (A), selected based on receiver operating characteristic curve analysis) indicated that there were six dystonic muscles (R RF, R HS, L IL, R IL, L LP, R LP), all of which were confirmed clinically.

R, right; L, left; medial hamstring (MHS), rectus femoris (RF), hamstring (HS), tibialis anterior (TA), gastrocnemius (GC), peroneus longus* (PL), iliopsoas* (IL), lumbar paraspinal (LP). * indicates fine-wire electrode.

Figure 4.

The standard deviations from A) the mean MdPF and B) the mean %AUC_{Total} for eight muscles were pooled from all subjects and measurement variability was assessed. The upper and lower bounds of the box are the 25th and 75th percentile, and the vertical distance spanned by the box is the interquartile range (IQR). The thick horizontal line within each box indicates the median value. The whiskers connect the maximum and minimum points that are within 1.5 IQR of the 25th and 7th percentiles, and open circles (○) indicate outliers that are beyond 1.5 IQR. Trial-to-trial measurement variability of spectral parameters is minimal.

R, right; L, left; rectus femoris (RF), tibialis anterior (TA), gastrocnemius (GC), peroneus longus* (PL). * indicates fine-wire electrode.

Table 1

Clinical characteristics of subjects.

Subject	Gender	Age (years)	Height (m)	Body Mass (kg)	BMI (kg/m ²)	Diagnosis	Muscles exhibiting clinical signs of dystonia *
1	M	16	1.74	65	22	Right anterior compartment syndrome	R/L MHS, L LHS
2	F	38	1.72	62	21	Foot drop	R GX, R/L GD, L RF
3	F	6	1.27	24	15	Dystonia	L GX, L GD, R TA, R/L GC, R/L PL *
4	F	55	1.63	90	34	Left knee instability	R/L PT, R EDL *, R PL *
5	F	16	1.67	48	17	Myoclonus with dystonia	R TA
6	F	17	1.74	59	20	Left foot drop	L GC
7	F	17	1.69	61	21	Abnormal gait	R/L HS, R/L RF
8	F	9	1.38	31	16	Left sided pain	R/L GX
9	F	50	1.66	105	38	Abnormal gait	R HS, R RF, R/L IL *, R/L LP, R/L GD
10	F	12	1.59	41	16	Abnormal gait	R RF, R HS, R TA
AVE (SD)		24 (18)	1.61 (0.16)	59 (25)	22 (8)		

R, right; L, left; extensor digitorum longus (EDL), gastrocnemius (GC), gluteus maximus (GX) and medius (GD), hamstrings (HS), medial and lateral hamstrings (MHS and LHS), iliopsoas (IL), lumbar paraspinals (LP), peroneus longus (PL), rectus femoris (RF), tibialis anterior (TA), and tibialis posterior (TP).

* indicates fine wire electrode.

Table 2

Calculated sensitivity, (1-specificity), and Youden index (J) for threshold frequencies between 40 and 80 Hz are shown. J is the vertical distance between each point and the receiver operating characteristic curve due to random chance (diagonal line from (0, 0) to (1, 1)); a larger J indicates better diagnostic performance. A threshold of 70 Hz is associated with optimal diagnostic performance.

MdPF Cut-off (Hz)	1-Specificity	Sensitivity	J
40	0.10	0.30	0.20
50	0.12	0.41	0.29
60	0.21	0.51	0.30
70	0.33	0.73	0.40
80	0.51	0.86	0.35