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Age and Electromyographic Frequency Alterations during Walking in Children with Cerebral Palsy

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Abstract

The use of surface electromyography (sEMG) recorded during ambulation has provided valuable insight into motor development and changes with age in the pediatric population. However, no studies have reported sEMG differences with age in the children with cerebral palsy (CP). In this study, data from 50 children were divided retrospectively into four groups, representing either an older (above the age of 7 years) or younger (below the age of 7 years) age group with either typical development (TD) or CP. Data were analyzed from 16 children in the younger age group with TD, and eight in the older age group with TD. Data were also available from 14 in the younger age group with CP, and 12 in the older age group with CP. SEMG signals from the rectus femoris (RF) and medial hamstring (MH) were analyzed using wavelet techniques to examine time-frequency content. RF muscle activity was statistically different between all groups ($p < 0.001$), with an elevated instantaneous mean frequency (IMNF) in the older TD group than the younger TD group, an elevated IMNF in the younger CP group than the older CP group, and elevated IMNF in both CP groups compared to both TD groups. Activity for the MH muscle followed the same pattern except for the CP young and old group comparison, which indicated no difference. The results indicate that differences in neuromuscular activation exist between younger and older groups of children with both TD and CP, and may provide new insight into muscle activity pattern changes during the development of walking.

Keywords

Electromyography; cerebral palsy; aging

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Introduction

The use of surface electromyography (sEMG) recorded during the performance of a functional activity, such as gait, has provided valuable insight into motor development and differences in muscle activation patterns with age in the pediatric population. Sutherland and colleagues [1], in a landmark study, defined the activation patterns (on/off patterns) of the lower extremity muscles during gait in children with typical development (TD) between the ages of 1 and 7 years, and established that after 3 years of age, muscle activation patterns were similar to those of adults. Likewise, a more recent study [2] in an older group of children and adolescents (3-18 years) with TD reported no relationship between age and muscle activity onset time, cessation time, or duration for a majority of lower extremity muscles during gait.

While muscle activation differences with age have been examined in the pediatric population with TD, no such studies have been reported for the pediatric population with cerebral palsy (CP). It has been demonstrated that there is a strong correlation between muscle activity and function in children with CP across multiple studies [3,4], and also that there is a decline in ambulatory status as children with CP mature into adults [5-7]. Thus, differences in muscle activity would be expected but have not been examined in younger children with CP. Examination of muscle activation patterns in younger children may give clinicians and researchers a greater understanding of how abnormal muscle activation patterns develop into the gait deviations observed in children with CP. Additionally, more advanced techniques of EMG analysis are now available [3,4] to investigate differences in signal amplitude and frequency, rather than only temporal information (onset/offset times). These techniques have demonstrated sensitivity to change in muscle function after hamstring surgery in children with CP while temporal information did not change [8].

The purpose of this study was to examine differences with respect to age in muscle activity (time-frequency components) using established wavelet analysis techniques in children with CP and children with TD. It was hypothesized that differences in the time-frequency characteristics would be evident in both groups as a function of age, and that the differences in the time-frequency characteristics would depend on whether the children had TD or CP.

Methods

Subjects

The data presented in this study were collected from 50 children enrolled in two separate protocols. The first study was an examination of hip and trunk muscle activity in early walkers with and without CP. The second study was an examination of the feasibility of wavelet analysis of muscle activity for children with CP. The parents of all the children signed a university institutional review board approved consent form, and the children gave verbal assent, or written assent if over the age of seven. The data was divided into four groups, representing either an older (above the age of 7) or younger (below the age of 7) age group with either TD or CP. Data were analyzed from 24 children with TD; 16 in the younger age group (mean age 3.4, range: 1 to 6 years, 9 females and 7 males) and 8 in the older age group (mean age: 11.2, range 8 to 13 years, 5 females and 3 males). Data were also available for 26 children with CP; 14 in the younger age group (mean age 4.9, range: 2 to 7 years, 5 females and 9 males) and 12 in the older age group (mean age: 10.8, range 8 to 14 years, 6 females and 6 males). The children with CP in both studies were classified as a Level II (impaired ambulation over distances) or Level III (use of assistive devices) on the Gross Motor Function Classification Scale [9].

Data acquisition

The two studies from which the sEMG data were pooled involved the analysis of the sEMG signals during gait, but focused on different sets of muscles. However, between the two studies, sEMG data were available from the rectus femoris (RF) and the medial hamstring (MH) muscles bilaterally. Surface electrodes for the RF and MH muscles in both studies were placed in the area of greatest cross sectional area, in a direction parallel to the muscle fibers. The MH electrode was located midway along a line from the ischial tuberosity and the medial condyle of the tibia, while the RF electrode was placed midway along a line from the anterior superior iliac spine to the superior patellar border. For the older children, the sEMG data was acquired with the Motion Lab Systems MA-310 surface EMG recording system (Baton Rouge LA). The sEMG signals were collected at a sampling rate of 1.2 kHz, with a preamplifier gain of 20 and bandpass filtering between 20 and 350 Hz. For the younger children, the Myomonitor III (Delsys Inc., Boston, MA) was used with a sampling rate of 1.2 kHz, and a preamplifier gain of 10, and bandpass filtering between 20 and 450 Hz.

Data Analysis

The sEMG data from the muscles were processed in MATLAB (The MathWorks Inc., Natick MA, USA). Before any analysis was performed, all raw data were low passed filtered using a 2nd order Butterworth filter with phase correction and a cutoff of 350 Hz. This was done to match the frequency ranges of the sEMG signals between the two studies. A time-frequency analysis was performed using the techniques as outlined in [3], but are reviewed here for clarity in presentation.

In this study, five complete gait cycles, defined by foot strike to ipsilateral foot strike, from the right side and from the left side were extracted from the sEMG data. All the recorded sEMG signals for the RF and MH muscles for each gait cycle were resampled to 1000 points representing the gait from 0% to 100% in 0.1% increments. The MATLAB *resample* command was used which applied a least-square linear phase FIR filter to the resampling process to prevent aliasing, with a separate FIR filtering process to prevent phase delay. The sEMG signals were then analyzed with the continuous wavelet transform (CWT) using MATLAB and the Time-Frequency Toolbox [10]. The CWT describes a series of mathematical techniques that can be used to analyze a complex time series signal with variable power or magnitude in a wide range of frequencies [11]. The strength of the CWT, in contrast to the Fourier transform, is the CWT extracts power and frequency information from the signal using specialized functions (referred to as mother wavelets), but can maintain the original timing information. Thus, time, frequency and amplitude characteristics of the sEMG signal all can be preserved and used for further analysis.

The CWT was applied to each sEMG signal using the Morlet wavelet as the mother function, defined as:

$$\Psi_0(\eta) = \pi^{-0.25} e^{i\omega_0\eta} e^{-\eta^2/2} \quad (1)$$

where η represents a nondimensional time parameter and ω_0 is the nondimensional frequency [12]. The Morlet was selected for use, with an increasing linear scale of between 1 and 126 to encompass all frequencies between 0.1 and 500 Hz, based upon the results from previous work on using the CWT to examine sEMG signals in children with CP [12]. The output of the CWT analysis is a scalogram, which is a three-dimensional representation of the analysis where time (% gait cycle) is on the x-axis, frequency (scale) is on the y-axis, and power (magnitude) is on the z-axis. The reduction of the three-dimensional scalogram to a time-frequency curve was

performed by calculating the mean frequency for each gait cycle interval using the following equation:

$$\text{IMNF}(t) = \int f * P(t, f) df / \int P(t, f) df \quad (2)$$

Where $P(t, f)$ represents the range of powers at a given frequency at each interval of the gait cycle, and f represents the frequency range of the EMG signal. The calculation of the mean frequency at each time interval, referred to as the instantaneous mean frequency curve (IMNF), was selected as the representative value of the frequency spectra across time since mean frequency has been used in the past to characterize muscle fatigue and activation level [13]. Thus, by calculating the mean frequency at each time interval, a representative curve of muscle activity over time is generated.

A functional principal component analysis (PCA) was completed using the IMNF curves from all the gait cycles to assess if the muscle IMNF curves across the four groups differed and at what intervals of the gait cycle [14]. The PCA is a mathematical least squares maximization procedure that transforms a large number of correlated variables (IMNF curves for all participants) into a smaller number of uncorrelated variables (regions of variability across the gait cycle) called principal components. This allows for variability across an entire curve to be captured in a small subset of principal components. The first principal component (PC) accounts for as much of the variability in the entire data set as possible, and each succeeding component accounts for the maximum of the remaining variability. Each individual IMNF curve (for each participant) is then assigned a weight for each PC. The value of the weight describes the degree of agreement or disagreement between the individual IMNF curve and the group variance identified by that particular PC. To assess if the muscle IMNF curves generated from the four groups differed, and at what regions of the gait cycle, the PC weights were averaged for each group and tested using a Welch statistic to determine if the means between the groups were equal. Individual group differences were assessed using Tamhane's T2 multiple comparison test ($\alpha = 0.05$).

Results

The comparison across all four groups for the RF and MH muscles is represented in Figure 1. The PCA generated four principal components (PCs) that were able to account for 97 to 99% of the variability between the groups. For the RF muscle, the differences between IMNF curves for all four groups were statistically significant for all four PC ($p < 0.001$). The children with TD in the older group had a significantly elevated IMNF curve than the younger group, and more clearly defined periods of activation by increases in frequency. In comparison, the children with CP in both the younger and older groups had IMNF curves with frequency values that were significantly elevated in comparison to both TD groups. The children in the older CP group exhibited a decreased frequency in the IMNF curve across the gait cycle in comparison to the younger CP group.

The MH muscle IMNF curve was statistically different for all four PCs ($p < 0.001$) for the younger and older TD groups, demonstrating the same increase in frequency and more clearly defined periods of activation in the older group. The two groups of children with TD were also significantly lower than both of the groups of children with CP, but there was no difference ($p > 0.285$ or greater for all four PCs) between the younger and older groups of children with CP.

Discussion

The purpose of this study was to examine differences in muscle activity (time-frequency components) using established wavelet analysis techniques in a group of children with CP and a group of children with TD with respect to age. While the timing of muscle activity during gait does not change after the age of three years in the pediatric population with typical development [1] alterations in muscle composition and size, in addition to the ongoing neural changes with age, indicate that patterns of muscle activity are dynamic and may follow a natural progression until full maturation is achieved. Understanding the dynamics of muscle activity in the pediatric population with TD enhances our understanding of the differences attributable to age rather than to impairments in a population with a neuromuscular disorder, such as in children with CP. The loss of function as the child with CP ages is well documented [5,6] and understanding how this relates to underlying muscle activity may help guide clinical treatment.

In order to interpret the findings from this study, the assumption was made that in an increase in mean frequency represented increased muscle recruitment. However, while this has been assessed in healthy adults [15], the relationship between frequency, motor unit composition and muscle activation is unstudied in children or in children with CP. The older children with TD exhibited larger mean frequency of the sEMG signal for the RF and MH muscles, with less variable activation times compared to young children with TD. This elevated frequency may be due to an increased size of the motor units recruited, increased rate coding of motor unit activation, and/or an increased number of motor units recruited [16]. As a larger magnitude of muscle force would need to be required to move or stabilize the larger body segments during gait as the child got older, this increase in frequency, reflecting increases in fiber recruitment, is anticipated.

The pattern observed in the children with TD is in direct contrast to the RF muscle in the children with CP, who demonstrated a higher sEMG frequency component in the younger group compared to the older group with CP. This suggests that at the younger age in CP, the motor strategy was continuous motor unit activation without distinct phases of activity and little rate or time coding, but that with learning and maturation some timing characteristics had been acquired, although activity remained elevated compared to TD peers. In both groups with CP, the frequency content of the sEMG signal was well above even the older group with TD, and the patterns were much less synchronous. While elevated frequencies suggest greater muscle activation, this does not mean efficient muscle recruitment. The IMNF curves may reflect impaired neuromuscular activation, as has been demonstrated in several studies examining isometric contractions in children with CP [17,18]. Since the children with CP may have been unable to recruit higher threshold motor units, and unable to drive lower threshold motor units to higher firing rates, the elevated frequency characteristics with lack of synchronous activity during gait may be a reflection of the near continuous activation of a smaller number of motor units within the muscle. While coordinated activation improves somewhat with aging, the results here appear to suggest that interventions focusing on improving muscle timing and coordination could prove to be beneficial in establishing more effective activation patterns as children with CP age. Improving muscle timing may also contribute to increased efficiency of movement, reducing the metabolic demands of excessive muscle activity, in addition to gains in functional mobility. This is especially true for the RF muscle, since it plays such a critical role in generating the appropriate forces for functional activities such as transfers, climbing stair, and playing.

The MH muscle exhibited a fairly consistent pattern of activation in the children with CP regardless of age, although the level of activation was much higher in children with CP than both groups of children with TD. Given the well-documented finding of spasticity in the hamstrings in children with CP [19-21] the muscle's force generating capabilities may be

impacted and greater activation (elevated frequency) necessary to offset the relative mechanical inefficiency or increased co-contraction of antagonist muscle groups in children with CP. Further, the higher activation levels may mask or negate measureable age-related differences in activation patterns of this muscle. This pattern of activation may lead to increased fatigability, knee pain, and increased energy expenditure during walking as a result of the increased muscle forces which are required to stabilize the knee during stance [22-24]. These results suggest that interventions which focus on increasing the activity of the antagonistic knee extensors or decreasing the activity of the MH at an early age may be beneficial in changing gait performance in children with CP, but additional research is needed to confirm this hypothesis.

These findings of age related changes in the pediatric population with and without CP need to be interpreted cautiously due to several limitations in the study. The first limitation was that the sEMG data for the two groups were collected with two different systems. Although off-line corrections were made to the data to allow for frequency comparisons, the possibility still exists that the use of 2 different data collection systems influenced the results. In addition, the results of this study need to be taken with caution given the retrospective nature of this study. The primary objective of the studies from which the data was collected was not to focus on age related changes. Thus, representations of subjects in the four groups were not balanced in regards to overall numbers, gender, and average age. A prospective study of these muscles and other muscles of the hip, trunk, and lower extremities in a group of children with a wider age range taking into account gender and pubertal status, and using the same data collection system, is warranted to determine if the trends reported here remain.

Conclusion

The introduction of time and frequency sEMG analyses using wavelet techniques enhances the understanding of muscle activity, and has the potential to provide additional insight into how muscle activation patterns change with age between the normal and pathological condition. In this study, the analysis of the sEMG signals from the RF and the MH muscle in children with TD as a function of age indicated that muscle activity as represented by sEMG is a dynamic process that may relate to the underlying changes in muscle structure or function that occur with aging. For the pediatric population with CP, differences in muscle activity with age are evident, and may also be muscle-specific, which may impact development of the reported loss of function as they age.

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Figure 1.

Comparison of the rectus femoris and medial hamstring activity for the children with Cerebral Palsy and the children with Typical Development in the younger and older age groups.