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Repeatability of surface EMG during gait in children

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Abstract

Although mean amplitude and ON–OFF timing of muscle recruitment and electromyography (EMG) activation during gait is achieved by an age of six to eight years in normally developing children, recruitment dynamics illustrated by the shape of the EMG waveform may require continued developmental practice to achieve a stable pattern. Previous analyses have quantified the repeatability of the EMG waveform in adult subjects, but EMG variability for a pediatric population may be significantly different. The goal of this study was to quantify intra-session and inter-session variability in the phasic EMG waveform patterns from the lower limb muscles during self-selected speeds of walking in healthy-normal children for comparison with adult variability in gait EMG. The variance ratio quantifies the repeatability of the integrated EMG waveform shape in a group of normally-developing children. Results reveal that between-session EMG waveform variability were similar in adult and pediatric populations, but within-session variability for the children was approximately twice the published value for adults. Clinical implications of this pediatric EMG variability suggest cautious interpretation of data from limited trial samples or inter-session changes in performance of gait data.

Keywords

Electromyography; Human locomotion

1. Introduction

Surface electromyography (EMG) recorded from the lower limb musculature is commonly obtained during clinical gait analysis in both pediatric and adult populations. These signals represent the excitation level of the muscles of the lower limbs during the walking activity [24]. EMG is recorded during gait to provide insight into muscle recruitment patterns and neuromuscular control of walking. Diagnostic assessment and treatment decisions may be based in part upon the EMG behavior associated with the dynamics of gait. However, these data are typically results of a limited number of walking trials from an assessment session. It is therefore, important to recognize the natural variability associated with these physiologic signals during free walking in order to improve the interpretation of EMG activity.

The mature pattern of muscle recruitment and EMG activation during gait is achieved by an age of six to eight years in normally developing children. Previous studies [21] have recorded EMG patterns to describe the period of time during the gait cycle when the EMG signal was

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ON or OFF. Results [22] concluded the ON–OFF pattern of EMG timing for the major thigh and leg muscles were well established prior to the age of seven. Differences between mature and immature gait are characterized by (1) greater co-contraction during stance phase in an immature gait pattern compared to improved reciprocal activation in fully developed gait patterns, and (2) improved integration of descending and stretch-reflex activities in mature gait patterns. These mature patterns are typically established before age seven with trends toward increased monosynaptic inhibition and polysynaptic development [4,5]. However, classifying the myoelectric performance from these data is limited by inter-subject and intra-subject variability.

Repeatability of lower limb EMG data during gait has not been established for a pediatric population. Shiavi et al. [20] demonstrated that coefficient of variability in adult subjects ranged from 50% to 88%. This variability increased when subjects were required to walk abnormally slow [20,21]. Preferred walking speeds generated improved repeatability. At preferred walking speeds the total energy of the EMG curve, i.e. mean EMG value averaged across the gait cycle, has been shown to be highly consistent [2]. However, the phasic behavior of the signal, i.e. the timing, rising and falling, relative signal amplitude, and the shape of integrated EMG waveform are typically of greater interest than cycle-mean amplitude. Unfortunately, this phasic behavior may be more variable than the mean amplitude and requires greater effort for quantification.

The variance ratio (VR) was established as a useful means of evaluating EMG variability [11]. A VR of zero represents no variability, i.e. perfect repeatability, and a VR of one represents a fully stochastic behavior. Kadaba et al. [13] demonstrated the VR of lower limb EMG in adult subjects were on the order of 0.21 for within-day performance and 0.52 for between-day performance recorded from surface electrodes. Hence, adult phasic EMG patterns are repeatable within a test session but more variable between test-days. The goal of this study was to quantify intra-session and inter-session variability in the phasic EMG waveform patterns from the lower limb muscles during self-selected speeds of walking in children. Although mean walking patterns are fully developed at a relatively young age, measures of kinematic variability indicate control patterns continue to develop into adulthood [9]. Hence, we hypothesized that EMG waveform repeatability in normally developing children must be less than adult EMG repeatability.

2. Methods

Eleven healthy, normal children (aged 6.5 ± 2.3 years) with no known gait related pathologies agreed to participate in the study. Subjects were instructed to walk across an instrumented walkway at a freely selected speed on 10 same-day trials, i.e. 10 trials recorded within a single experimental session. Subjects returned for second day of testing within approximately seven days of the first visit and the procedures were identically repeated. To assure processing methods were similar to the adult data reported in the literature [13], we also collected and processed within-session EMG repeatability data from 10 healthy adult subjects who performed 10 repeated trials in a single-session evaluation. Prior to participation in the study, subjects and guardians of the children signed informed consent approved by the University of Virginia Institutional Review Board.

EMGs were recorded from both left and right lower limbs during each trial. The EMG were synchronized with gait kinematics and timing recorded from an instrumented, pressure sensitive walkway (GAITRite, CIR Systems Inc., Clifton, NJ) with an active area of 0.6 m wide and 3.6 m long. To assure steady state walking behavior subjects were required to walk the entire length of a 10 m walkway with the instrumented carpet in the center. Muscle activity from the rectus femoris (RF), medial hamstring (MH), anterior tibialis (AT) and medial

gastrocnemius (MG) muscles were recorded bilaterally from bipolar surface electrodes. EMG data were bandpass filtered from 15 Hz to 450 Hz in hardware (Noraxon USA Inc., Scottsdale, AZ) and sampled at 1000 Hz with software processing included rectifying and filtering (Hanning weighted low-pass filter 15 Hz equivalent-noise bandwidth). Signals were normalized in amplitude by scaling the EMG data to achieve a unit total energy under the EMG signal, i.e. the area under the processed EMG curve was equal to one. The time base of the EMG was reported from 0% to 100% of the stride-duration in 1% increments.

The variance ratio (VR) was used to quantify the repeatability of the EMG waveforms. The VR is insensitive to mean EMG amplitude, comparing instead the repeatability of the processed EMG waveform shape. The VR has been described in detail elsewhere [7,13]. Briefly, the VR as proposed by Hershler and Milner [11] computes the between-trial (or between-day) variance at each normalized time increment summed over the entire gait cycle and divided by the total variance.

$$VR = \frac{\sum_i \sum_j \left(E_{ij} - \bar{E}_j\right)^2 / m(n-1)}{\sum_i \sum_j \left(E_{ij} - \bar{E}\right)^2 / (mn-1)}$$

where $i = 1 \ldots m$ is the trail number (or day), $j = 1 \ldots n$ the time epoch within each gait cycle, E_{ij} the EMG value of trial number (day) i at time j, $\bar{E}_j$ the mean EMG value at time epoch j over all trials (days), and $\bar{E}$ is the grand mean EMG signal. Clearly, separate VR values can be achieved to assess within-session, i.e. between-trial, and between-session repeatability. The VR values may range from 0 to 1, where a value of 0 indicates identically repeatable waveforms (no variability), and a value of 1 indicates dissimilar waveforms (poor repeatibility). This method was selected to compare results with published repeatability data from adult populations using identical analyses [13].

3. Results

Cadence, stride length and velocity for both the adult and pediatric population were within normal levels (Table 1) and similar to published values [12]. Percent of gait cycle spent in single-support, double-support, and swing phase were not statistically different between the two groups. Clearly owing to increased leg length the stride length and velocity were greater in the adult group.

Mean variance ratios describing the EMG variability or repeatability in the children ranged from 0.328 to 0.657 (Table 2). The rectus femoris (RF) demonstrated greater variability than the other measured muscles; the medial hamstrings (MH) demonstrated the greatest repeatability. Statistical analyses of VR values revealed significant ($p < 0.01$) differences between these muscles (Table 3). Post hoc analyses revealed no statistical difference between the mean VR values of the anterior tibialis (AT) and medial gastrocnemius (MG) groups. Significant muscle-by-side interactions suggest the ankle muscles, i.e. the AT and MG, were more variable on the right than left leg whereas the thigh muscles, i.e. RF and MH, demonstrated the opposite trend. Both within-session and between-session VR demonstrated these trends. Because VR of some muscles was increased on the right leg and others increased on the left side, as a main effect for between session. VR was not significant for the numbers of subjects studied.

To test whether processing methods and associated results were similar to previously published data we collected and processed within-session EMG VR from 10 adults and compared them with results from Kadaba et al. [13]. Statistical analyses revealed no significant differences in

VR values for muscle or side for the adult data. The results of the adult data are similar to the within-session values reported in the literature, i.e. within one standard deviation (Table 4). Surface EMG in normally developing children were less repeatable in within-session analyses than those of normal adults, i.e. higher VR values. This was demonstrated by a significant main effect for age (Table 3). Comparison of pediatric data to adult within-session VR of Kadaba et al. [13] confirmed this difference. Post-hoc analyses revealed an age difference in all muscles except the MH group, which was the muscle demonstrating the least variability in the pediatric group. Thus, the results support the conclusion that within-session EMG variability in children is approximately twice the adult variability.

Between-session repeatability was similar in the pediatric and published adult populations. Kadaba et al. [13] reported a mean between-session VR of 0.530 similar to the pediatric value of 0.474 ± 0.12 from the current study. Between-session and within-session VR values were not significantly different in the pediatric population. An exception was noted in the RF wherein the within-session variability (VR = 0.551 ± 0.12) was slightly smaller than the between-session VR (0.590 ± 0.08), achieving statistical significance in the repeated-measures ANOVA. This is in contrast to published adult data demonstrating significantly improved repeatability during within-session performance compared with between-session repeatability [13]. Hence, despite greater within-session variability results suggest between-session repeatability for this population of children was similar to adult repeatability.

4. Discussion

Interpretation of EMG data may be the most challenging component of a gait assessment, but can also provide remarkable insight into the neuromotor control describing the kinetic and kinematic aspects of locomotion. The challenge of interpreting dynamic EMG is further complicated by variability in the data [12]. A primary consideration in functional performance is the ability to successfully complete a specific motor task and perform it consistently. This latter aspect is often overlooked in clinical interpretation. There is reason to believe from literature in other biomechanical and motor control arenas that consistent performance and control of a task may be an important quantifiable factor when describing pathology or rehabilitative progress [17], including analyses demonstrating differences in pathologic classifications [8]. Consistent performance requires developmental time and practice. It should not be surprising, therefore, that achieving repeatable EMG recruitment patterns requires greater development than demonstrating mature mean performance. However, it is noteworthy that stable locomotion may be achieved despite significant variability in the muscle recruitment patterns [6].

Although a mature gait pattern may be established by the early age of 6 to 8 years on average [4,5,21,22], variability about that mean performance, i.e. fine control, continues to develop for many years. Published data [13] illustrate that adult EMG waveforms can change from day-to-day, VR = 0.52, but are reasonably repeatable within a single test session, VR = 0.21. Current results demonstrate children perform with similar day-to-day variability as the adults, VR = 0.48. However, unlike the adult population, the children performed with similar levels of EMG variability within a session as between days with approximately twice the within-day waveform variance of the adults.

Right leg versus left leg differences were observed. Recognizing that right or left dominant preferences exist one might expect this behavior, but severe asymmetric difference must reduce total system performance [1]. It is interesting to note, therefore, that the multi-joint segment may compensate. The leg has redundant degrees-of-freedom in its role of power transfer so that locomotor control may be achieved via a wide range of recruitment strategies between segments or joints [10,18,23]. Muscles controlling ankle function were more variable on the

right than left leg. Conversely the hip and knee muscles including the RF and MH were more variable on the left than on the right. Bernstein [6] suggests variability within a joint may be filtered through intersegmental coordination. It is nonetheless curious that variability may be asymmetric. Analyses of the inter-joint coordination may be indicative of motor performance and control [3,15,16,19] and may be of clinical value pending continued research in this area.

It remains unknown when a mature EMG recruitment repeatability level is achieved. One might expect the VR level to improve with development, demonstrating extreme variability when gait is first achieved and slowly becoming more repeatable with age. Conversely, variability in the children may indicate more responsive stabilizing control than in adults. It may be possible that the young neurocontrol system can withstand greater variability thereby allowing more degrees of freedom for control. The current analyses were limited in sample size and age range wherein the children were approximately six years old and the adult population included healthy young volunteers, primarily college age individuals. To better understand the development of myoelectric control strategies a broader range of age categories must be studied in future efforts. It is possible the control variability may continue to change into the geriatric ages. Thus, it may be feasible to characterize a performance criteria based upon control consistency in terms of electromygraphic patterned age. The current results also suggest the number of repeated trials necessary to represent an individual's gait performance may best be assigned as a function of developmental age [2].

Evaluation of EMG waveform variability is well determined by the VR measure. The method is both simple to achieve and robust in terms of EMG processing techniques [7]. Current results from the adult population agree remarkably well with published data [13] indicating excellent potential for inter-study or inter-institutional comparisons. There are no reasons to suspect the mathematical technique is susceptible to anthropometric confounding and, therefore, permits comparisons between disparate populations. Recording factors such as skin-electrode impedance, electrode placement and signal cross-talk may contribute to increased variability particularly in regard to day-to-day variability. However, these techniques are typical of clinical assessment protocols and, therefore, results are representative of pediatric gait evaluations. EMG data may be readily compared between population groups if normalization issues in the form of signal amplitude and timing are circumvented [14,25], potentially by using techniques such as the principle components analyses [26] to evaluate waveform shape and the variance ratio to evaluate waveform variability. Hence, evaluation of pathologic gait may be assisted by further efforts to study recruitment using these nonparametric techniques to compare VR in children with cerebral palsy (CP) with normally developing, age matched individuals. There remains a dichotomous opinion whether children with CP might demonstrate more or less recruitment variability. These hypotheses should be tested in future research.

In conclusion, within-session variability of the EMG waveforms from a population of normally developing children was approximately twice the level of healthy adults. The clinician/researcher must be cautioned when evaluating myoelectric changes between evaluation session to determine if changes seen in muscle activation are directly attributable to a specific treatment intervention. Caution is also warranted when interpreting EMG data from a limited number of within-session trials. Although it is agreed that cycle-mean and ON–OFF timing for EMG activity may be established and repeatable by an early age [21,22], EMG waveform shape potentially illustrate continued development of muscle recruitment patterns into the adult years.

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Table 1

Mean (± S.D.) spatial temporal parameters

	Children	Adults
Cadence (steps/min)	129.8 ± 18	115.5 ± 10
Stride length (cm)	110.0 ± 19	135.3 ± 8.2
Velocity (cm/s)	118.9 ± 31	131.0 ± 13.1
Single leg support (%)	38.9 ± 1.6	37.3 ± 1.1
Stance (%)	58.7 ± 2.6	60.5 ± 2.0

Table 2

Within-session and between-session variance ratios (mean ± S.D.)

Muscle	Within-session			Between-session		
	Right	Left	Average	Right	Left	Average
RF	0.530 ± 0.09	0.572 ± 0.14	0.551 ± 0.12	0.524 ± 0.04	0.657 ± 0.03	0.590 ± 0.08
MH	0.328 ± 0.15	0.440 ± 0.16	0.384 ± 0.17	0.343 ± 0.08	0.460 ± 0.13	0.401 ± 0.12
AT	0.521 ± 0.18	0.414 ± 0.11	0.468 ± 0.16	0.521 ± 0.07	0.420 ± 0.05	0.433 ± 0.10
MG	0.505 ± 0.14	0.349 ± 0.14	0.427 ± 0.16	0.520 ± 0.05	0.346 ± 0.05	0.470 ± 0.08

Table 3

Statistical ANOVA of results from separate analyses of within-session VR and between-session VR

	***p*-value**	
	Within-session	**Between-session**
Muscle	<0.001	<0.001
Side	<0.003	<0.416
Age	<0.001	
Muscle × side	<0.038	<0.001
Muscle × age	<0.679	
Side × age	<0.027	

Table 4

Comparison of within-session VR from adults and literature values (mean ± S.D.)

Muscle	Adults (*n* = 10) within-session	Kadaba et al. (*n* = 10) within-session	Kadaba et al. (*n* = 10) between-session
RF	0.270 ± 0.13	0.267	0.563
MH	0.203 ± 0.14	0.172	0.503
AT	0.199 ± 0.11	0.255	0.480
MG	0.173 ± 0.15	0.197	0.576