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Repeatability of electromyography recordings and muscle synergies during gait among children with cerebral palsy

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ABSTRACT

Background: Clinical gait analysis is commonly used in the evaluation and treatment of children with cerebral palsy (CP). While the repeatability of kinematic and kinetic measures of gait has previously been evaluated, the repeatability of electromyography (EMG) recordings or measures calculated from EMG data, such as muscle synergies, remains unclear for this population.
Research question: Are EMG recordings and muscle synergies from clinical gait analysis repeatable between visits for children with CP?
Methods: We recruited 20 children with bilateral CP who had been referred for clinical gait analysis. The children completed two visits less than six weeks apart with EMG data collected bilaterally from five muscles (rectus femoris, medial hamstrings, vastus lateralis, anterior tibialis, and medial gastrocnemius). Variance ratio and cosine similarity were used to evaluate repeatability of EMG waveforms between visits. Nonnegative matrix factorization was used to calculate synergies from EMG data at each visit to compare synergy weights and activations.
Results & significance: The inter-visit variance ratios of EMG data for children with CP were similar to previously reported results for typically-developing children and unimpaired adults (range: 0.39 for vastus lateralis to 0.66 for rectus femoris). The average cosine similarity of the EMG waveforms between visits was greater than 0.9 for all muscles, while synergy weights and activations also had high similarity – greater than 0.8 and 0.9 between visits, respectively. These results demonstrate that EMG repeatability between visits during clinical gait analysis for children with CP is similar to unimpaired individuals. These results provide a baseline for evaluating whether observed changes in EMG recordings between visits reflect real changes in muscle activity or are within the range of inter-visit variability.

1. Introduction

Clinical gait analysis is used to evaluate impaired movement in children with cerebral palsy (CP). The information from these analyses – including kinematics, kinetics, and electromyography (EMG) data – are used to guide treatments and evaluate outcomes [1–3]. Since these data are often used for longitudinal analyses, understanding repeatability between visits is critical to determine whether changes over time reflect changes in an individual's movement patterns, expected variations between days, or experimental errors. While the repeatability of kinematic and kinetic measures from clinical gait analyses has been well documented, and generally demonstrate good repeatability [4–6], similar analyses of EMG data for children with CP have not been previously reported.

Muscle activity monitored with EMG recordings can provide insight into impaired neuromuscular control. Clinical gait analyses currently collect EMG data to identify muscles with excessive activity [7], evaluate spasticity [8,9], or detect inappropriate patterns of co-activation [10]. By combining EMG data with kinematics, kinetics, and physical exam measures, clinicians can identify muscles that should be targeted for surgical interventions, provide guidance for therapy, or evaluate the impact of interventions such as spasticity management [11–13].

While EMG data from a single muscle can provide insight for targeted interventions, prior research has indicated that the activation

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patterns of multiple muscles can provide additional insight into impaired movement. Recent research has used muscle synergy analyses to evaluate impaired neuromuscular control for children with CP [14,15]. Synergies, also commonly referred to as motor modules or modes, are calculated from EMG data and describe groups of muscles that are commonly activated together. For unimpaired individuals, 4–6 synergies can typically describe over 95% of the variance in EMG activity during walking, running, or other activities [16–18]. In CP, the number of synergies required to reach this threshold (henceforth simply called "number of synergies") is reduced, suggesting that children with CP use a simplified control strategy compared to typically-developing (TD) peers. Children with CP whose synergies are more similar to TD peers generally have higher function and better outcomes after treatment compared to children with more simplified control [15,19,20].

Prior research of unimpaired adults has suggested that surface EMG recordings during gait are repeatable across days. In a series of studies, Kadaba and colleagues [21,22] demonstrated that EMG profiles during unimpaired adult gait had good intra-visit repeatability and were "*quite repeatable*" between visits – adequate for informing clinical decisions, although they cautioned that future work should develop "*a profile of repeatability characteristics for different groups of patients*." Granata et al. (2005) extended these results to TD children and demonstrated that, although stride-to-stride variability in EMG data was nearly twice that of unimpaired adults, the inter-visit repeatability was similar [23].

While no prior research has investigated EMG repeatability for children with CP, we previously evaluated the repeatability of synergies in a small, retrospective study. We analyzed synergies for five children with CP and six TD children and found the variance accounted for by a given number of synergies and synergy weights were similar between visits [28]. While these results demonstrated that synergies might provide a promising measure for evaluating neuromuscular control in CP, further research is required to evaluate the generalizability of these results and repeatability of the underlying EMG data used to calculate synergies.

The goal of this research was to evaluate the inter-visit repeatability of muscle activity and synergies during clinical gait analysis for children with CP. We recruited 20 children with bilateral CP and evaluated the repeatability of EMG and synergies during clinical gait analysis from two visits less than six weeks apart. Quantifying this repeatability is critical to understand the value of these measures in clinical gait analysis for evaluation and treatment planning.

2. Methods

This research was reviewed and approved by the University of Minnesota's Institutional Review Board and all participants provided consent. We recruited 20 children with bilateral CP who were referred for gait analysis at Gillette Children's Specialty Healthcare (Table 1). Each child underwent a standard clinical gait analysis, including collection of EMG data, as well as a second analysis within six weeks to evaluate inter-visit repeatability of EMG data and synergies.

2.1. Electromyography data

At both visits, surface EMG data were collected bilaterally from five muscles (RF: rectus femoris, MH: medial hamstrings, VL: vastus lateralis, AT: anterior tibialis, and GAS: medial gastrocnemius). This set of muscles and the following data collection procedures followed the standard of care at this clinic. Data were collected from a minimum of three barefoot walking trials at self-selected speed. All participants walked independently, without walkers or crutches. Each trial typically included 3–5 strides. EMG data from each limb (Motion Laboratory Systems, Baton Rouge, LA, USA) were sampled at 1080 Hz, high-pass filtered at 25 Hz, rectified, and low-pass filtered at 10 Hz [21,24]. Data from the middle 80% of each walking trial were included in the analyses to avoid periods of acceleration and deceleration during the beginning and end of each trial. EMG data for each muscle were normalized to the maximum value across all trials at each visit.

Table 1
Participant characteristics.

	Sex	GMFCS Level	Age	Height (cm)	Mass (kg)	Time* (days)	Speed (m/s) Visit 1	Visit 2
1	M	1	10.3	129.4	21.8	21	1.11	1.09
2	F	3	8.8	115.0	21.2	37	0.26	0.35
3	M	2	6.2	99.5	18.9	25	0.57	0.48
4	M	2	12.9	163.7	73.2	28	0.71	0.65
5	F	1	11.0	152.0	43.7	41	1.11	1.13
6	M	1	11.5	137.6	22.8	42	1.22	1.15
7	F	3	7.4	122.3	22.4	1	0.48	0.78
8	F	2	8.9	131.5	29.7	21	0.86	0.98
9	M	3	7.8	117.5	24.3	1	0.55	0.44
10	M	3	7.0	106.8	19.8	27	0.63	0.76
11	M	2	13.2	145.7	34.3	1	1.07	1.29
12	M	2	11.5	140.3	41.2	22	0.78	0.93
13	M	1	13.6	150.0	47.4	1	0.99	0.98
14	M	2	10.7	129.7	27.7	23	0.68	0.55
15	F	3	13.2	131.4	46.7	33	0.56	0.60
16	M	2	13.0	160.5	60.7	1	0.74	0.82
17	M	2	10.2	131.2	25.5	24	1.10	1.05
18	F	2	8.5	131.5	29.5	2	1.08	0.96
19	M	3	10.4	124.0	23.6	1	0.72	0.65
20	M	1	12.8	154.0	40.1	17	1.08	0.97
		AVE	**10.4**	**133.7**	**33.7**	**18**	**0.81**	**0.83**
		SD	**2.3**	**17.2**	**14.7**	**15**	**0.27**	**0.26**

Age, height, & mass at Visit 1. *Time between visits

Two metrics were used to evaluate EMG repeatability: variance ratio and cosine similarity. Variance ratio has been used extensively in prior literature to evaluate EMG repeatability [21,23] and provides a measure of the relative similarity of waveforms over a number of cycles. While variance ratio is sensitive to the average magnitude and degree of modulation for a given muscle, cosine similarity provides a complementary measure that captures the difference or angle between two vectors or waveforms. For these analyses, we identified initial contact events and re-sampled the processed EMG data to 101 points over each gait cycle. Initial contact events were identified with a custom Matlab (MathWorks, Inc., Natick, Massachusetts, United States) script that used the velocity of heel and toe markers to identify periods when each foot was in contact with the ground. The average EMG signal over all gait cycles was calculated for each muscle and visit.

Intra- and inter-visit repeatability were evaluated using the variance ratio (VR):

$$VR = \frac{\sum_{i=1}^{t}\sum_{j=1}^{g}(E_{ij}-\bar{E}_i)^2/t(g-1)}{\sum_{i=1}^{t}\sum_{j=1}^{g}(E_{ij}-\bar{E})^2/(tg-1)}$$

where t is the number of time points ($t = 101$ for each gait cycle), g is the number of gait cycles, E_{ij} is the EMG signal of gait cycle j at time point i, $\bar{E}_i$ is the average EMG signal at time point i over all gait cycles, and $\bar{E}$ is the average EMG magnitude over all gait cycles. Smaller VR values indicate greater similarity between gait cycles. Similar to prior studies, the intra-visit VR was calculated by comparing each gait cycle to the average of each visit, while the inter-visit VR was calculated by comparing each gait cycle to the average across both visits.

Cosine similarity (CS), also referred to as the un-centered correlation coefficient, was calculated as the dot product of two vectors, normalized by the product of the vector lengths:

$$CS = \frac{\vec{E_g}\cdot\vec{\bar{E}}}{\|\vec{E_g}\|\ \|\vec{\bar{E}}\|}$$

where g is the number of gait cycles, $\vec{E_g}$ is the EMG data for gait cycle g, and $\vec{\bar{E}}$ is the average EMG data across gait cycles. Since the processed EMG data is strictly positive, CS is bounded between 0 and 1, with values closer to 1 indicating greater similarity. Intra-visit CS was calculated by comparing each gait cycle to the average of each visit and then taking the average across all gait cycles, while the inter-visit CS was calculated by comparing all gait cycles to the average across visits.

2.2. Synergy analysis

To calculate synergies, the processed EMG-data from the middle 80% of all walking trials at each visit were concatenated to maximize the amount of data for analysis, while avoiding periods of acceleration and deceleration [25]. Synergies were calculated and compared for each leg. Since synergies can be sensitive to the amount of data included in the analysis, the visit with the minimum amount of EMG data was determined for each participant and the same number of data points were analyzed for both visits. Note that one participant (P10) did not have EMG data from the GAS during the first visit, so this participant was excluded from the synergy analyses. Nonnegative matrix factorization (NNMF, Matlab, MathWorks Inc., Natick, Massachusetts, United States) was used to calculate synergies from the EMG data (settings: 50 replicates, 1000 maximum iterations, 1×10^{-4} minimum threshold for convergence, and 1×10^{-6} threshold for completion) [26]. Briefly, NNMF identifies for a given number of synergies (n), the synergy weights (W), and synergy activations (C) that describe the greatest variation in the EMG data such that:

$$EMG = W^{*}C + error$$

W is an m x n matrix where m is the number of muscles (*i.e.*, $m = 5$) and C is an n x t matrix where t is the number of time points. The total variance accounted for by $n = 1$–4 synergies ($tVAF_n$) was calculated for each visit as [27]:

$$tVAF_n = 1 - \frac{\|EMG - W^{*}C\|^2}{\|EMG\|^2}$$

To evaluate synergy repeatability, we calculated the number of synergies required to describe over 95% of the variance in EMG data for each visit and also compared $tVAF_n$, W, and C between visits for each number of synergies ($n = 1$–4). Cosine similarity was used to evaluate the similarity of the synergy weights and activations from each visit, using the same equation as above where the EMG data vector is replaced with W or C. While concatenated EMG data were used to calculate synergies for each visit, the synergy activations (C) were divided into gait cycles for comparison between visits ($t = 101$ points). The average synergy activations across gait cycles were calculated for each visit and compared by calculating the CS for each participant. An example of the EMG data for a representative participant illustrates the step-to-step variability and resulting synergies for both visits (Fig. 1).

3. Results

Intra-visit repeatability of EMG data was similar to previous studies of TD children (Table 2). The RF (average ± standard deviation, VR: 0.53 ± 0.18) and AT (VR: 0.48 ± 0.18) demonstrated the greatest variation between gait cycles within a visit. The intra-visit CS indicated that the EMG waveforms were highly similar, with an average CS greater than 0.90 for all muscles (Table 3, Fig. 2). The CS was only less than 0.80 for one muscle of one subject (P14 left VL = 0.70), and was greater than 0.90 for 92% of cases (*i.e.,* 10 muscles collected for 20 subjects).

Inter-visit repeatability of EMG data was similar to prior results from both TD children and unimpaired adults (Table 2). The inter-visit VRs were greater than the intra-visit results, as would be expected due to variations in EMG placement, walking patterns, and other factors between days. The VL had the lowest inter-visit VR (0.40 ± 0.20), while the RF had the greatest inter-visit VR (0.65 ± 0.18). The average inter-visit CS was still greater than 0.9 for all muscles, indicating that the EMG waveforms were highly similar across gait cycles at both visits (Table 3, Fig. 2). Examining the inter-visit CS of each participant, the CS occasionally dropped below 0.80 for a single muscle, which might indicate a change in electrode placement or other differences between visits. However, of the 200 cases analyzed (10 muscles for 20 subjects), the inter-visit CS was greater than 0.90 for 82% of the muscles examined.

Muscle synergies calculated from EMG data were similar between visits (Fig. 2). Similar to prior studies [15,20], total variance accounted for by $n = 1$–4 synergies was higher among the children with CP compared to previous reports of unimpaired gait. The average total variance accounted for by one synergy ($tVAF_1$) was 81.41 ± 5.52% for the children with CP. The average absolute change in $tVAF_1$ between visits was 4.24 ± 3.09%. The average number of synergies required to describe over 95% of the variance in EMG activity was 3.1 (range 2–4). The number of synergies required to describe over 95% of the variance in EMG data changed between visits for six participants (4 increased, 2 decreased).

The synergy weights and activations were similar between visits (Fig. 3). For the two, three, and four synergy solutions, respectively, the average CS of the synergy weights was 0.89 ± 0.10, 0.83 ± 0.11, and 0.90 ± 0.08 and the average CS of the synergy activations was 0.93 ± 0.06, 0.91 ± 0.06, and 0.92 ± 0.05.

4. Discussion

The intra- and inter-visit repeatability of EMG data during gait for children with CP was similar to previous results for TD children. Similar to TD children analyzed by Granata et al. [23], the intra-session VRs of the children with CP presented here were nearly double that of unimpaired adults – reflecting that children have greater step-to-step variability in muscle activity during gait than adults. While one might hypothesize that intra-session VR would decrease with age as a child's gait pattern matures, we observed only weak correlations between age and intra-session VR in CP (age range: 6.2–13.2 years, $R^2 < 0.2$ comparing intra-session VR and age for each muscle). The high VRs of EMG during gait in children highlights the importance of observing multiple gait cycles during clinical gait analyses. Plotting multiple gait cycles can help clinicians capture and understand the inter-step variability in muscle recruitment patterns for children with CP for evaluation and treatment planning.

While intra-session VR was greater for children with CP than unimpaired adults, inter-session VR was similar to both TD children and unimpaired adults. These results suggest that EMG data across visits can be compared in CP with similar confidence and fidelity as unimpaired gait. The inter-session VR of children with CP, TD children, and unimpaired adults ranges between 0.4–0.7. Average intra-session and inter-session CS were greater than 0.9 for all muscles analyzed in this study, indicating that although EMG data can exhibit variability between gait cycles and visits, that the similarity of waveforms is still high compared to the myriad potential ways an individual could modulate their muscle activity. These results also support prior research in children with CP that has noted minimal changes in EMG activity after treatments such as single-event multi-level orthopaedic surgery [29,30]. Overall, these results demonstrate that EMG signals are repeatable between visits during gait for children with CP, but demonstrate variance between gait cycles similar to TD children that should lead clinicians and researchers to exercise caution in over-interpreting small changes in EMG recordings.

Synergies calculated from EMG data were also similar between visits for children with CP. While the number of synergies is one of the most common measures used to evaluate synergies, these results highlight the limitations of using an arbitrary threshold to define a given "number" of synergies for each individual. While six participants demonstrated a "change" in synergy number between visits, the absolute change in tVAF between visits was not different for these participants compared to those whose number of synergies did not change. For example, $tVAF_3$ was 95.5% and 93.9% at visits one and two for P01, which would be interpreted as a change in synergy number, although

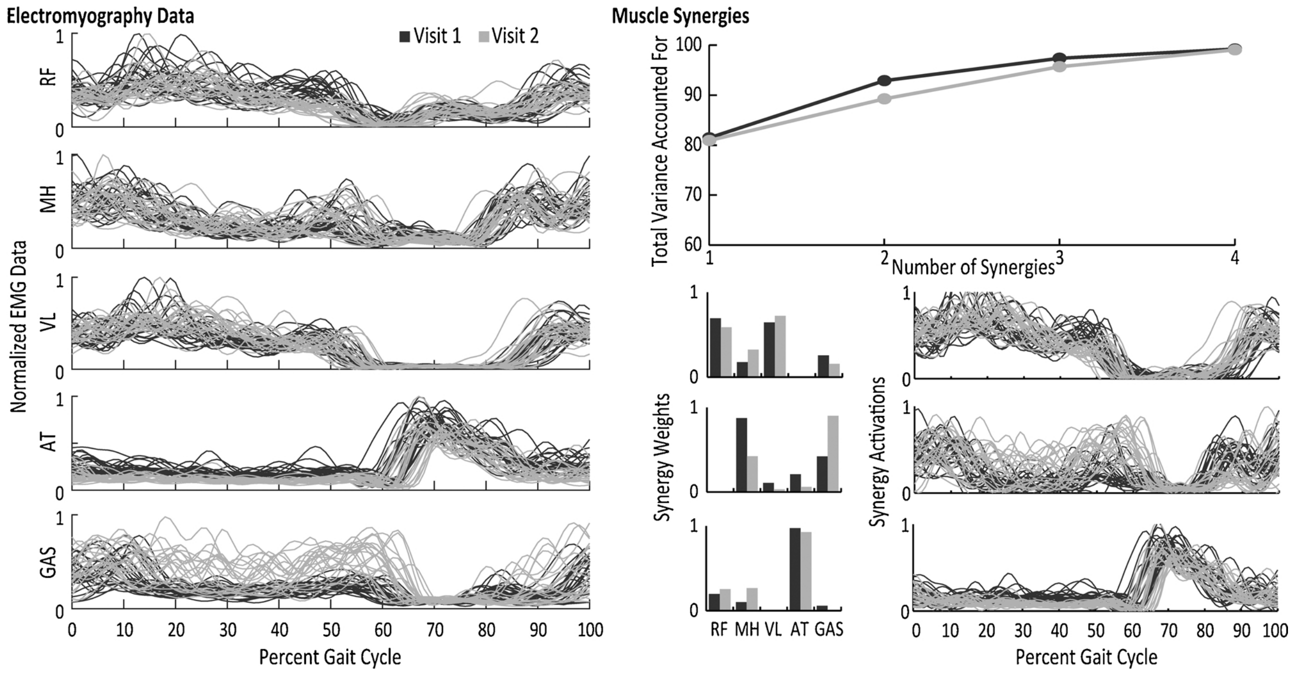

Fig. 1. Example of EMG data and muscle synergies of all gait cycles for each visit from the right leg of one participant. EMG data were collected from five muscles from each leg and normalized to the gait cycle to evaluate intra-visit and inter-visit repeatability. EMG data from all gait cycles were concatenated and NNMF was used to calculate synergies. For this participant, three synergies were required to describe over 95% of the variance in EMG data on the right leg at both visits with a similarity of 0.91 and 0.95 for synergy weights and activations, respectively.

the absolute change in tVAF was small. As demonstrated by both this and our prior study [28], comparing $tVAF_n$ directly provides a more repeatable measure than picking a threshold to define a given number of synergies. From these results, the minimal detectable changes in tVAF between visits at a 90% confidence interval for five muscles were 5, 2.5, 1.5, and 1.2% for $n = 1$–4 synergies, respectively. Prior research has used $tVAF_1$ as a summary measure of synergy analyses and this minimal detectable change is less than the average difference of 10 percentage points in $tVAF_1$ between TD and CP children [15,20]. Further, a 10–15 point lower $tVAF_1$ (more similar to TD peers) has been associated with clinically significant improvements in walking speed and Gait Deviation Index after surgery in children with CP [19].

Synergy weights and activations were also repeatable between visits for children with CP during gait, with an average CS greater than 0.8 and 0.9, respectively. These results are similar to our prior retrospective study of six TD children and five children with CP which found synergy weights had a correlation coefficient greater than 0.7 for two or more synergies between days, but did not evaluate synergy activations [28]. Due to the variability in synergy weights and activations between children with CP, we did not analyze the repeatability of individual synergies (*e.g.,* synergy dominated by plantarflexor muscles). However, despite the heterogeneity in synergies between subjects, the inter-session repeatability of synergies was high for individual children with CP and supports potential uses in treatment planning or rehabilitation.

In this research, we evaluated EMG repeatability for children with bilateral CP who were referred for clinical gait analysis. However, our sample did not include children with unilateral CP or children who used

Table 3
Cosine Similarity (average ± S. D.).

Electromyography Muscle	Intra-Session CP Children	Inter-Session CP Children
RF	0.94 ± 0.03	0.93 ± 0.08
MH	0.95 ± 0.03	0.93 ± 0.07
VL	0.95 ± 0.04	0.93 ± 0.10
AT	0.95 ± 0.02	0.93 ± 0.08
GAS	0.95 ± 0.02	0.96 ± 0.04
Synergies Number (n)	**Inter-Session Weights**	**Inter-Session Activations**
1	0.95 ± 0.04	0.98 ± 0.02
2	0.89 ± 0.10	0.93 ± 0.06
3	0.83 ± 0.11	0.91 ± 0.05
4	0.90 ± 0.08	0.92 ± 0.05

Table 2
Variance Ratio (average ± S. D.).

	Intra-Session Variance Ratio				Inter-Session Variance Ratio		
Muscle	CP Children (N = 20)	TD Children* (N = 11)	Adults* (N = 10)	Adults** (N = 10)	CP Children (N = 20)	TD Children* (N = 11)	Adults** (N = 10)
RF	0.53 ± 0.18	0.53 ± 0.09	0.27 ± 0.13	0.27	0.65 ± 0.18	0.52 ± 0.04	0.56
MH	0.41 ± 0.19	0.33 ± 0.15	0.20 ± 0.14	0.17	0.50 ± 0.20	0.34 ± 0.08	0.50
VL	0.32 ± 0.18			0.19	0.40 ± 0.20		0.48
AT	0.48 ± 0.18	0.52 ± 0.18	0.20 ± 0.11	0.26	0.60 ± 0.18	0.52 ± 0.07	0.48
GAS	0.41 ± 0.17	0.51 ± 0.14	0.17 ± 0.15	0.20	0.50 ± 0.20	0.52 ± 0.05	0.58

Variance ratio averaged across legs and visits.
*Results from Granata et al., (2005), right leg.
**Results from Kadaba et al., (1985).

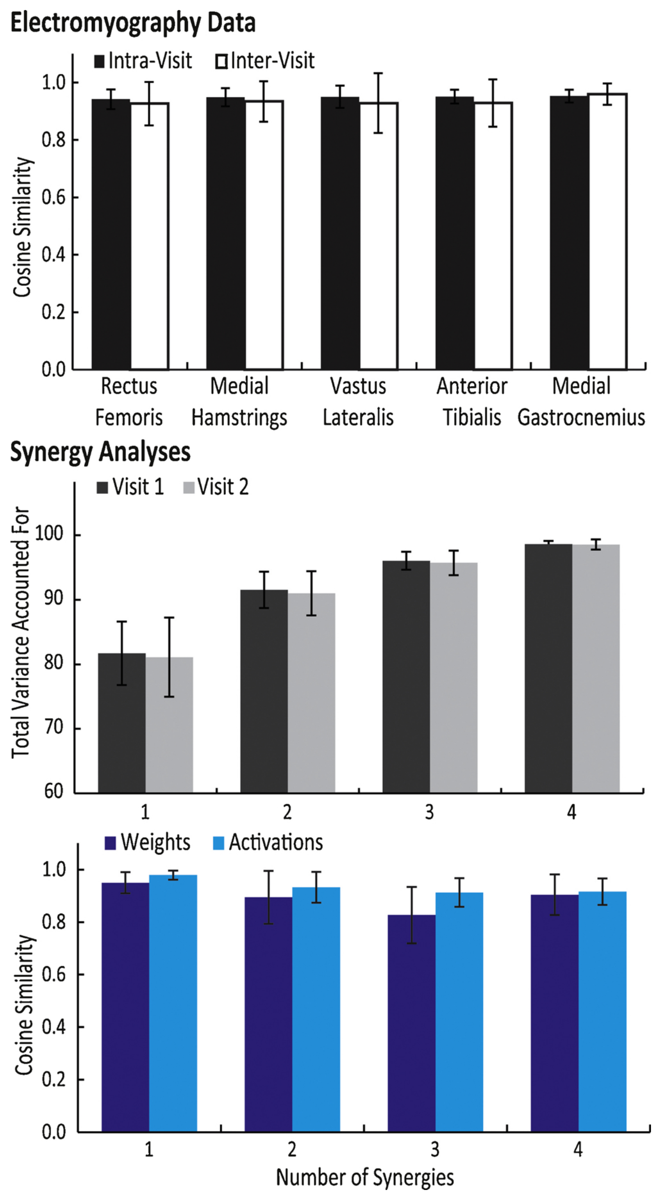

Fig. 2. (Top) Average intra-visit and inter-visit cosine similarity of EMG data and synergies across all participants. **(Middle)**The total variance accounted for by a given number of synergies (tVAFn) at each visit. (**Bottom**) Average cosine similarity of synergy weights and activations between visits across all participants. The averages of the right and left legs are shown.

assistive devices, such as walkers or crutches, which could impact EMG repeatability. We did not enforce a specific walking speed and allowed for up to 6 weeks between visits. Thus, these results reflect repeatability over multiple weeks, including variability in self-selected walking speed between visits. We did observe a modest impact of walking speed on VR (R^2 = 0.1–0.4 comparing intra-session VR to walking speed), such that children who walked faster had lower VRs. However, we observed no correlation ($R^2 < 0.05$) between inter-session VR and the number of days between visits. Deciding how to normalize EMG magnitude between visits remains a challenge. Since maximum voluntary contractions are neither feasible nor commonly used for children with CP, we normalized EMG magnitude to the peak value across all trials at each visit. This normalization scheme may mask changes in muscle activity between visits, such as after surgical interventions or botulinum toxin injections. Determining improved methods for normalizing EMG magnitude in clinical populations is an important area for future research.

This study demonstrated that children with CP and TD children exhibit similar levels of intra- and inter-visit repeatability for muscle recruitment and coordination. While EMG recordings have been in the toolkit for clinical gait analysis for decades, understanding the repeatability of EMG-based measures is critical to inform and support future use and interpretation. This research provides a baseline for evaluations that aim to alter muscle activity, track changes over time, or evaluate the impact of surgical or rehabilitation interventions for children with CP.

Conflict of interest

The authors have no conflicts of interest to disclose related to this work.

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