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Repeatability of muscle synergies within and between days for typically developing children and children with cerebral palsy

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ABSTRACT

Muscle synergies are typically calculated from electromyographic (EMG) signals using nonnegative matrix factorization. Synergies identify weighted groups of muscles that are commonly activated together during a task, such as walking. Synergy analysis has become an emerging tool to evaluate neuromuscular control; however, the repeatability of synergies between trials and days has not been evaluated. The goal of this study was to evaluate the repeatability of synergy complexity and structure in unimpaired individuals and individuals with cerebral palsy (CP). EMG data were collected from eight lower-limb muscles during gait for six typically developing (TD) children and five children with CP on two separate days, over three walking speeds. To evaluate synergy complexity, we calculated the total variance accounted for by one synergy ($tVAF_1$). On a given day, the average range in $tVAF_1$ between gait cycles was 18.2% for TD and 19.1% for CP. The average standard deviation in $tVAF_1$ between gait cycles was 4.9% for TD and 5.0% for CP. Average $tVAF_1$ calculated across gait cycles was not significantly different between days for TD or CP participants. Comparing synergy structure, the average (standard deviation) within day correlation coefficients of synergy weights for two or more synergies were 0.89 (0.15) for TD and 0.88 (0.15) for CP. Between days, the average correlation coefficient of synergy weights for two or more synergies was greater than 0.89 for TD and 0.74 for CP. These results demonstrate that synergy complexity and structure averaged over multiple gait cycles are repeatable between days in both TD and CP groups.

1. Introduction

How the human body controls muscle activity to coordinate complex movements remains an open question and an important area of research. In cyclic motions, such as walking, prior research has theorized that the nervous system controls a lower dimensional system composed of weighted groups of muscles, rather than controlling each muscle individually [1]. These weighted groups of muscles are commonly referred to as synergies or modes. Synergies are commonly estimated from experimental electromyography (EMG) data using matrix factorization algorithms [2], such as nonnegative matrix factorization (NNMF). These algorithms identify groups of muscles that are consistently activated together during a given task [3,4].

In unimpaired individuals, only a small set of synergies (e.g., $n = 4–6$) are required to reproduce measured EMG signals during balance, walking, and various other tasks [3–6]. Recent research has used synergies as a framework to evaluate altered neuromuscular control in individuals with neurologic disorders, such as stroke or cerebral palsy (CP) [7–9]. These studies have demonstrated that individuals with neurologic disorders use fewer synergies during walking compared to unimpaired individuals, suggesting a simplified control strategy that may contribute to impaired movement [7,9,10]. Synergies may be clinically useful for evaluating impaired neuromuscular control or predicting patient-specific responses to treatment [11–14]. For example, Routson et al. [15] found that synergies measured before a treadmill training program in adult stroke survivors were associated with changes in synergy structure, complexity, and timing after training and were also related to improvements in gait.

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These studies suggest that synergies may be clinically useful for diagnosis and treatment planning. However, before the clinical potential can be evaluated, the repeatability of synergies needs to be quantified. Repeatability of synergies between steps and between days has not yet been investigated among individuals with neurologic disorders such as stroke or CP. Natural variability between steps may cause significant changes in muscle activity [16], and may impact the clinical utility of synergy analyses. Past studies have used a number of methods to address this variability, including averaging EMG data over multiple trials [17–19], or concatenating EMG data from multiple gait cycles prior to calculating synergies [4,7,20]. Oliveira et al. [16] found concatenation of EMG data from multiple gait cycles improved synergy representation of muscle activity in subsequent gait cycles compared to EMG data averaged over multiple gait cycles.

In this study, our goal was to examine the repeatability of synergies, for both typically developing (TD) children and children with CP. We hypothesized synergies would be repeatable between days for both TD and CP. Further, we hypothesized that, due to neuromuscular impairments, children with CP would display less repeatability between steps compared to TD. The results of this study will help inform how synergies can be used to evaluate neuromuscular control for potential clinical applications.

2. Methods

We retrospectively analyzed repeatability of synergies for a group of six TD children and five children with CP who had previously received repeated gait analyses with EMG data (Table 1). The children with CP had mild impairment, Gross Motor Function Classification System (GMFCS) Level I. Three of the children with CP had a primary diagnosis of spastic diplegia and two of the children with CP had a primary diagnosis of spastic hemiplegia (one left and one right side impairment). Kinematics at the self-selected speed were near normal except for P9 (apparent equinus per Rodda et al. [21]) and P11 (hemiplegia, group 0 per Riad et al. [22]).

For each individual, retrospective EMG and motion capture data was analyzed for nine trials on two separate days (i.e., 18 total trials). The second data collection occurred an average of 8.5 days after the initial data collection (range 2–23 days). For children with CP, this time interval normally corresponded to a follow-up visit to discuss the results of the gait analysis. Each individual walked at three walking speeds: self-selected walking pace, a fast pace, and as fast as possible without running. The number of gait cycles collected over the trials on each day varied between participants due to differences in walking speed, step length, and quality of marker data. The average number of gait cycles analyzed for TD participants on a day was 44.8 (SD: 15.9), with a range of 25–78 cycles, and 47.5 (19.6), with a range of 24–81 for CP participants. Two trials for one TD participant from the first day contained missing marker data and were excluded from analyses.

Table 1
Study population.

Subject	Gender	Age (years)	Mass (kg)	Height (m)	Diagnosis
Typically developing					
P1	M	6	24.7	1.25	–
P2	M	13	47.6	1.60	–
P3	F	13	63.4	1.66	–
P4	M	15	59.0	1.79	–
P5	M	6	20.2	1.20	–
P6	F	9	26.9	1.31	–
Avg (SD)	–	10.3 (3.5)	40.3 (17.1)	1.5 (0.2)	–
Cerebral palsy					
P7	M	11	54.8	1.56	Sp D
P8	F	11	33.6	1.30	Sp D
P9	F	13	45.0	1.60	Sp D
P10	M	10	28.3	1.35	H-L
P11	M	6	21.0	1.22	H-R
Avg (SD)	–	10.2 (2.3)	46.5 (12.0)	1.4 (0.1)	–

Sp D = Spastic diplegia; H-L = Hemiplegia with left affected limb; H-R = Hemiplegia with right affected limb.

EMG data were recorded at two laboratories within the same hospital using a 16-channel system (Wave Wireless EMG, Cometa, Milan, Italy) at either 1000 or 1500 Hz and were synchronized with a 10- or 15-camera motion analysis system (VICON, Oxford Metrics, Oxford, UK) recording at 100 Hz. The EMG data were high pass filtered with a 4th order Butterworth with a 40 Hz cut-off, rectified, and low pass filtered at 4 Hz [7]. EMG data were collected from eight muscles per leg including the gluteus medius, lateral hamstrings, medial hamstrings, vastus lateralis, rectus femoris, gastrocnemius (lateral head), soleus, and tibialis anterior. Both legs were analyzed for the TD participants and participants with diplegic CP, while only the affected side was analyzed for the participants with hemiplegic CP. Some trials contained poor EMG signal quality for a single muscle, which was excluded from the analysis for both days for those participants (impacting the right vastus lateralis for P1-P4, P8 and P11 and the left gluteus medius for P10). EMG data for each muscle was normalized to the maximum on a given day and segmented into gait cycles for each limb (measured initial contact to initial contact from motion analysis data). Each gait cycle was normalized to 101 data points.

Synergies were calculated from the EMG data using NNMF [2,23]. Briefly, NNMF decomposes experimental EMG data into a set of synergy weights (W_{mxn}) and synergy activations (C_{nxt}), such that EMG = W^*C + error, where n is the number of synergies, m is the number of muscles measured (7 or 8 in this study) and t is equal to the number of time points (101 over the normalized gait cycle for this study). Error is defined as the difference between the experimental EMG data and the reconstructed EMG data calculated by synergies. We calculated synergies with NNMF in Matlab (MathWorks, Inc., Natick, Massachusetts, United States) using the following parameters which produced repeatable synergies between trials of NNMF: 50 replicates, 1000 max iterations, 1×10^{-4} minimum threshold for convergence, and a 1×10^{-6} threshold for completion. For each gait cycle, we calculated both the synergy complexity, which describes the total variance accounted for ($tVAF_n$) in the muscle activity reproduced by synergies ($n = 1$ to 5), and the synergy weights or structure, which describe muscles commonly activated together.

For each participant, we evaluated synergy complexity by calculating the average and standard deviation of $tVAF_n$ (for $n = 1$ to 5 synergies) for each limb and each day (TD: 6 participants × 2 limbs × 2 days = 24 samples; CP: 3 diplegic participants × 2 limbs + 2 hemiplegic participants × 1 limb, × 2 days = 16 samples). Total variance accounted for was calculated as:

$$tVAF_n = \left(1 - \frac{\left[\sum_j^t \sum_i^m (\text{error})^2\right]}{\left[\sum_j^t \sum_i^m (\text{EMG})^2\right]}\right) \times 100\% \quad (1)$$

To determine repeatability of $tVAF_n$ between gait cycles, we evaluated the range and standard deviation of $tVAF_n$ values for both TD and CP groups. To determine the repeatability of $tVAF_n$ between days and with varying speeds, we used a linear mixed effects (LME) model to examine the fixed effects of group (i.e., TD versus CP), day, and cycle speed normalized by leg length, and random effects on intercept for each participant. The resulting LME equation was of the form:

$$tVAF_n \sim C_1 \times \text{Group} + C_2 \times \text{Day} + C_3 \times \text{Cycle Speed} + (1|\text{Subject}) \quad (2)$$