**Muscle synergies and complexity of neuromuscular control during gait in cerebral palsy**

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**AIM** Individuals with cerebral palsy (CP) have impaired movement due to a brain injury near birth. Understanding how neuromuscular control is altered in CP can provide insight into pathological movement. We sought to determine if individuals with CP demonstrate reduced complexity of neuromuscular control during gait compared with unimpaired individuals and if changes in control are related to functional ability.

**METHOD** Muscle synergies during gait were retrospectively analyzed for 633 individuals (age range 3.9–70y): 549 with CP (hemiplegia, n=122; diplegia, n=266; triplegia, n=73; quadriplegia, n=88) and 84 unimpaired individuals. Synergies were calculated using non-negative matrix factorization from surface electromyography collected during previous clinical gait analyses. Synergy complexity during gait was compared with diagnosis subtype, functional ability, and clinical examination measures.

**RESULT** Fewer synergies were required to describe muscle activity during gait in individuals with CP compared with unimpaired individuals. Changes in synergies were related to functional impairment and clinical examination measures including selective motor control, strength, and spasticity.

**INTERPRETATION** Individuals with CP use a simplified control strategy during gait compared with unimpaired individuals. These results were similar to synergies during walking among adult stroke survivors, suggesting similar neuromuscular control strategies between these clinical populations.

Walking is an important activity of daily living that enhances independence, participation, and quality of life. However, for individuals with cerebral palsy (CP), walking can be a challenging and sometimes impossible activity. To improve mobility for individuals with CP and other neurological disorders, we need to understand how unimpaired individuals control walking and how control is altered after brain injury.

There are several theories for how humans control movement. Rhythmic activities such as walking are theorized to be partly controlled at the level of the spinal cord. Infants, spinalized animals, and individuals who have had a spinal cord injury can produce rhythmic stepping patterns. However, in addition to rhythmic stepping, walking requires dynamic balance and adaptability. Thus, muscle activity controlled via the spinal cord is theorized to be supplemented with cortically modulated muscle activity producing a versatile gait pattern.

Computational techniques, including matrix factorization algorithms, have been used to evaluate the complexity of different neuromuscular control strategies. Using experimentally measured muscle activity (electromyography [EMG]), matrix factorization algorithms identify low-dimensional spaces composed of weighted groups of muscles that can describe variation in muscle activity. These weighted groups of muscles, commonly referred to as synergies or modes, represent muscles that are consistently activated together and are theorized to represent a simplified control strategy compared with controlling each muscle individually. Evaluating the variance in muscle activity accounted for by a given number of synergies can provide a measure of the complexity of control used by an individual during a task. Previous studies have shown that muscle activity during a variety of tasks can be described by a small set of synergies. For example, less than six synergies have been shown to describe over 90% of the variance in muscle activity during unimpaired gait. The term synergy has been used clinically in many contexts. In this manuscript we use the term synergy to refer to weighted groups of muscles identified mathematically from EMG data.

Previous studies have also demonstrated that synergies identified from EMG data are altered after brain injury. After a stroke, fewer synergies are used during walking and upper-extremity tasks compared with unimpaired adults.
stroke survivors found that individuals with synergies more similar to unimpaired adults had greater improvements in walking after a treadmill training program, suggesting synergy analysis may be useful for treatment planning.

In this study we analyzed a large population who had previously received clinical motion analysis. This provided a powerful group for evaluating synergies, but also introduced limitations. We were limited to the EMG data and clinical examination measures that are included as the standard of care. In particular, our measures of strength, spasticity, and selective motor control are all ordinal scales with poor sensitivity; other evaluations such as torque measurements for strength or the Tardieu Scale for spasticity could be superior. EMG data was only available from five muscles per leg. Synergies calculated with non-negative matrix factorization are sensitive to the number of muscles in the analysis, and using fewer muscles increases estimates of total VAF. These limitations motivated using the normalized walk-DMC as a summary measure of synergy complexity. Despite the limited number of EMG channels, the synergy weights, \( W_f \) of the unimpaired individuals were similar to previous studies of unimpaired adults.

Clinical motion analysis laboratories evaluate gait in individuals with CP, to inform surgical and rehabilitation planning. The results of this study demonstrated that synergies are altered among individuals with CP, and walk-DMC can provide a measure of altered neuromuscular control from data collected as part of clinical care. Future studies will determine if synergies change after treatment or predict clinical outcomes. The similarity of synergies in CP, stroke, and infant rhythmic-stepping indicates that there are common changes in control after brain injury that may reflect control in early development. Quantifying these changes and evaluating the plasticity of synergies may provide pathways to new treatments for individuals with CP and other neurological disorders.

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SUPPORTING INFORMATION
The following additional material may be found online:

**Figure S1:** Decrease in walk-DMC with GMFCS and FAQ levels across diagnosis subtypes.

**Figure S2:** Correlation of walk-DMC with clinical examination measures.

**Figure S3:** The relationship between walking speed and walk-DMC for unimpaired individuals.

REFERENCES
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