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

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ABBREVIATIONS

DMC	Dynamic motor control
FAQ	Gillette Functional Assessment Questionnaire
Walk-DMC	Dynamic motor control index during walking
VAF	Variance accounted for

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.[1] Infants, spinalized animals, and individuals who have had a spinal cord injury can produce rhythmic stepping patterns.[2–4] 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.[5] 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.[6,7] For example, less than six synergies have been shown to describe over 90% of the variance in muscle activity during unimpaired gait.[8] 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,[9,10]

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stroke survivors found that individuals with synergies more similar to unimpaired individuals had greater improvements in walking after a treadmill training program,[24] 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.[17] 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*, of the unimpaired individuals were similar to previous studies of unimpaired adults.[9]

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

1. Kiehn O. Locomotor circuits in the mammalian spinal cord. *Annu Rev Neurosci* 2006; **29**: 279–306.
2. Forssberg H. Ontogeny of human locomotor control. I. Infant stepping, supported locomotion and transition to independent locomotion. *Exp Brain Res* 1985; **57**: 480–93.
3. Grillner S, Zangger P. On the central generation of locomotion in the low spinal cat. *Exp Brain Res* 1979; **34**: 241–61.
4. Calancie B, Needham-Shropshire B, Jacobs P, Willer K, Zych G, Green BA. Involuntary stepping after chronic spinal cord injury. Evidence for a central rhythm generator for locomotion in man. *Brain* 1994; **117**: 1143–59.
5. Lee DD, Seung HS. Learning the parts of objects by non-negative matrix factorization. *Nature* 1999; **401**: 788–91.
6. Ting LH, Chvatal SA. In: Danion F, Latash ML, editors. Motor Control: Theories, Experiments, and Applications. New York, NY: Oxford University Press, 2010: 102–21.
7. Cheung VC, d'Avella A, Tresch MC, Bizzi E. Central and sensory contributions to the activation and organization of muscle synergies during natural motor behaviors. *J Neurosci* 2005; **25**: 6419–34.
8. Allen JL, Neptune RR. Three-dimensional modular control of human walking. *J Biomech* 2012; **45**: 2157–63.
9. Clark DJ, Ting LH, Zajac FE, Neptune RR, Kautz SA. Merging of healthy motor modules predicts reduced locomotor performance and muscle coordination complexity post-stroke. *J Neurophys* 2010; **103**: 844–57.
10. Cheung VCK, Turolla A, Agostini M, Silvoni S, Bennis C, Kasi P. Muscle synergy patterns as physiological markers of motor cortical damage. *Proc Natl Acad Sci U S A* 2012; **109**: 14652–6.
11. Li F, Wang Q, Cao S, Wu D, Wang Q, Chen X, editors. Lower-limb muscle synergies in children with cerebral palsy. 2013 6th International IEEE/EMBS Conference on Neural Engineering (NER); 2013 6–8 November; San Diego, CA: IEEE, 2013.
12. Rose J, McGill KC. Neuromuscular activation and motor-unit firing characteristics in cerebral palsy. *Dev Med Child Neurol* 2005; **47**: 329–36.
13. Nashner L, Shumway-Cook A, Marin O. Stance posture control in select groups of children with cerebral palsy: deficits in sensory organization and muscular coordination. *Exp Brain Res* 1983; **49**: 393–409.
14. Unnithan V, Dowling J, Frost G, Volpe AB, Bar-Or O. Cocontraction and phasic activity during GAIT in children with cerebral palsy. *Electromyogr Clin Neurophysiol* 1996; **36**: 487–94.
15. Schwartz MH, Rozumalski A, Trost JP. The effect of walking speed on the gait of typically developing children. *J Biomech* 2008; **41**: 1639–50.
16. Schwartz MH, Rozumalski A. The Gait Deviation Index: a new comprehensive index of gait pathology. *Gait Posture* 2008; **28**: 351–7.
17. Steele KM, Tresch MC, Perreault EJ. The number and choice of muscles impact the results of muscle synergy analyses. *Front Comput Neurosci* 2013; **7**: 105.
18. Palisano R, Rosenbaum P, Walter S, Russell D, Wood E, Galuppi B. Development and reliability of a system to classify gross motor function in children with cerebral palsy. *Dev Med Child Neurol* 1997; **39**: 214–23.
19. Novacheck TF, Stout JL, Tervo R. Reliability and validity of the Gillette Functional Assessment Questionnaire as an outcome measure in children with walking disabilities. *J Pediatr Orthop* 2000; **20**: 75–81.
20. Kendall H, Kendall F. Muscles: Testing and Function. Baltimore, MD: Williams and Wilkins, 1949.
21. Bohannon RW, Smith MB. Interrater reliability of a modified Ashworth scale of muscle spasticity. *Phys Ther* 1987; **67**: 206–7.
22. Rozumalski A, Schwartz MH. Crouch gait patterns defined using k-means cluster analysis are related to underlying clinical pathology. *Gait Posture* 2009; **30**: 155–60.
23. Ivanenko YP, Dominici N, Cappellini G, et al. Changes in the spinal segmental motor output for stepping during development from infant to adult. *J Neurosci* 2013; **33**: 3025–36a.
24. Routson RL, Clark DJ, Bowden MG, Kautz SA, Neptune RR. The influence of locomotor rehabilitation on module quality and post-stroke hemiparetic walking performance. *Gait Posture* 2013; **38**: 511–7.