The Influence of Selective Voluntary Motor Control on Terminal Swing Phase in Ambulatory Children with Cerebral Palsy

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Abstract

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Background

The ability to walk and keep up with peers is an important goal amongst children with cerebral palsy (CP) and their caregivers. Factors associated with decreased walking speed are of interest amongst clinicians and researchers. Decreased knee extension during the terminal swing phase of gait is one of a variety of factors that contributes to inadequate step length and ultimately, to walking speed. The aim of this study was to examine factors associated with the magnitude of knee extension during terminal swing phase, including a task-specific measure of selective voluntary motor control (SVMC), such as the Walking Dynamic Motor Control Index (walk-DMC). It was hypothesized that impaired SVMC of the swing limb, as measured by walk-DMC, and decreased stance phase stability, as measured by single limb support time of the stance limb, would be significant predictors of decreased magnitude of knee extension during terminal swing phase in the group with diplegia. It was hypothesized that impaired SVMC of the swing limb would be a significant predictor of decreased knee extension during terminal swing phase in the group with hemiplegia, whereby stability in stance phase of the uninvolved limb was less impaired.

Methods

The study involved a retrospective analysis of instrumented gait data, inclusive of surface electromyography (sEMG), from an accredited motion analysis laboratory between 2015 and 2024. Participants between the ages of 7-18 years with a diagnosis of diplegic or hemiplegic CP,

Gross Motor Function Classification System (GMFCS) levels I and II were included. A forward stepwise multiple linear regression model was used to predict the magnitude and the timing of knee extension during terminal swing phase. Predictors of interest included SVMC, as measured by walk-DMC, knee extension and ankle dorsiflexion joint range of motion (ROM), hamstring muscle spasticity, measures of knee extensor strength, and hamstring muscle-tendon lengthening characteristics of the swing limb, as well as single limb support time of the stance limb. GMFCS level and history of prior surgery were included as covariates.

Results

The final dataset used in the analysis included 90 individuals with diplegic CP (GMFCS level I, n = 35; GMFCS level II, n = 55) and 105 individuals with hemiplegic CP (GMFCS level I, n = 59; GMFCS level II, n = 46). SVMC, as measured by the walk-DMC, demonstrated a negative correlation with the magnitude of knee extension during terminal swing phase in both the group with diplegia ($r = -.39$, $p < .001$) and the group with hemiplegia ($r = -.31$, $p = .001$), such that better SVMC was associated with increased knee extension at terminal swing phase. Stance phase stability, as measured by single limb support time of the contralateral limb, was not significantly correlated with the magnitude of knee extension during terminal swing phase in the group with diplegia ($r = .01$, $p = .892$), while a positive correlation was observed in the group with hemiplegia ($r = .33$, $p < .001$). For the group with diplegia, the stepwise multiple regression model populated with walk-DMC, knee extension ROM, ankle dorsiflexion ROM, and extensor lag in the group with diplegia was statistically significant, $R^2 = .324$, $F(4, 85) = 10.195$, $p < .001$, adjusted $R^2 = .292$. The addition of GMFCS level and history of prior surgery, as covariates, led to a statistically significant increase in R^2 of .111, $F(2, 83) = 8.163$, $p < .001$. For the group with hemiplegia, the stepwise multiple regression model populated with walk-

DMC, single limb support time of the contralateral limb, and ankle dorsiflexion ROM in the group with hemiplegia was statistically significant, $R^2 = .251$, $F(3, 101) = 11.308$, $p < .001$, adjusted $R^2 = .229$. The model including the covariates of GMFCS level and history of prior surgery was not statistically significant (R^2 of .006, $F(2, 99) = .418$, $p = .660$).

Conclusion

Decreased knee extension in terminal swing phase in individuals with CP is multifactorial and is not simply the result of tight hamstrings or weak knee extensors. Impaired SVMC, as measured by walk-DMC, is a significant predictor of decreased knee extension during terminal swing phase. Including task-specific measures of SVMC, such as the walk-DMC, is essential when using instrumented gait analysis (IGA) in assessing gait pathology to inform clinical decision-making and predict outcomes following treatment.

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Dedication

This dissertation is dedicated to the memory of my beloved father, Michael L. "Mickey" Carotenuto, Sr. I am forever grateful for his selfless commitment to my pursuit of learning. JAJ

Introduction

Cerebral palsy (CP) is defined as a group of disorders associated with the development of movement and posture resulting in activity limitations, which are attributed to a non-progressive injury to the developing fetal or infant brain (Bax et al., 2005). Individuals with CP can be classified based upon their topographical distribution of involvement (e.g. hemiplegia, diplegia) as well as by their functional abilities. The Gross Motor Function Classification System (GMFCS), is a five-level ordinal scale, whereby those classified as level I can walk independently without the use of an assistive device and have difficulty with more advanced gross motor skills and those classified as level V are largely non-ambulatory (Palisano et al., 2008). Children with CP demonstrate limitations in selective voluntary motor control (SVMC), among other impairments, such as hypertonia, muscle weakness, and joint contractures. The findings from several research studies have suggested that reduced SVMC contributes more to impaired motor performance than other factors, such as hypertonia or contractures (Balzer et al., 2016). Injury to the periventricular white matter, as seen on magnetic resonance imaging (MRI), is one of the most common findings in individuals with spastic diplegia and has also been observed in those with hemiplegia and quadriplegia (Fowler et al., 2010). It is well understood that voluntary movement emerges from the activation of efferent motor signals, which descend through the corticospinal tracts (CSTs). Limitations in motor function exhibited by children with CP have been correlated with damage to the CSTs within the periventricular area (Cahill-Rowley & Rose, 2014; Fowler et al., 2010). Furthermore, organization of the lower extremity in the sensorimotor cortex results in an increased vulnerability of the CSTs associated with distal lower extremity muscles as compared to more proximal musculature. This finding has been supported by research which demonstrated an increased severity of SVMC impairment from proximal to distal joints (Fowler et al., 2010).

Several definitions have been offered to describe SVMC. The United States National Institutes of Health Pediatric Motor Disorders Taskforce defined SVMC as ‘the ability to isolate the activation of muscles in a selected pattern in response to demands of a voluntary movement or posture’ (Sanger et al., 2006). Others have defined SVMC as ‘obligatory coactivation of synergist muscles’ in an effort to differentiate abnormal coactivation of synergist muscles from normal recruitment patterns associated with stabilization of a limb or maintenance of balance. This definition also provides a distinction between obligatory synergist coactivation and other abnormal movement patterns seen in the setting of upper motor neuron lesions, such as spasticity.(Cahill-Rowley & Rose, 2014). The term ‘selective voluntary motor control’ is further defined as ‘the ability to perform isolated joint movement without using mass flexor/extensor patterns or undesired movement at other joints’ (Fowler & Goldberg, 2009). This definition of SVMC describes one’s ability to perform specific isolated joint movements upon request and does not include the ‘habitual activation of selected muscles during functional tasks’ (Fowler et al., 2010).

Impaired SVMC manifests in several different ways in children with CP. Alterations in the speed of movement or presence of mirror movements, observed as simultaneous associated movements at contralateral joints, are often seen upon clinical examination of SVMC (Fowler et al., 2009). The inability to activate an individual muscle group without concomitant activity of the antagonist musculature can result in errors of the timing of muscle recruitment during a given movement. Children with CP who exhibit impaired SVMC can have difficulty moving the hip, knee, and ankle joints independently of one another, which is demonstrated as mass patterns of flexion or extension (Fowler & Goldberg, 2009). Walking is an example of a functional activity in which SVMC is required, whereby hip flexion, knee extension, and ankle dorsiflexion occur simultaneously at terminal swing phase in preparation for initial contact (Cahill-Rowley & Rose, 2014; Fowler et al., 2009). Children with CP commonly exhibit deficits in knee extension at terminal swing phase, which can be due, in part, to impairments in SVMC (Fowler & Goldberg, 2009). Decreased knee extension in terminal swing phase can result in decreased step length, which can negatively impact gait velocity.

Clinicians and researchers alike agree that SVMC is an important prognostic factor of functional ability as well as of outcomes following interventions for individuals with CP (Fowler et al., 2009; Schwartz et al., 2016). Appropriate assessment methods are critical to further understand the influence of impaired SVMC on function in children with CP (Sardoğan et al., 2021). Increased knowledge in this area will only enhance clinical decision-making for this population (Dobson, 2010). While various clinical measures are available to assess SVMC, objectively quantifying motor control is challenging (Dobson, 2010; Schwartz et al., 2016).

Chapter 1: Selective Voluntary Motor Control

1.1 Assessment of Selective Voluntary Motor Control

There are a variety of clinical tools that have been described to assess selective voluntary motor control (SVMC). The Selective Control Assessment of the Lower Extremity (SCALE) was developed as an objective clinical assessment method of SVMC in children with cerebral palsy (CP). The tool can be administered in less than 15 minutes and does not require specialized equipment. Several factors associated with both understanding of corticospinal tract (CST) function as well as prior methods of assessment were considered in the creation of the SCALE. These included the 'ability to move each joint selectively, involuntary movement at other joints including the contralateral limb, ability to reciprocate movement, speed of movement, and generation of force as demonstrated by excursion within the available range of motion (ROM)'. The testing procedure involves the assessment of a reciprocal movement which does not involve mass flexion or extension for each of five joints of both lower extremities. A score of 'normal' (two points), 'impaired' (one point), or 'unable' (zero points) is given to each joint and total limb scores for both lower extremities are summated. A score of 'normal' SVMC for a joint is given when the reciprocal movement pattern is performed within a defined verbal cadence without concomitant movement observed at joints of the test limb or the contralateral side. A score of 'impaired' SVMC is given when isolated movement is only observed for part of the sequence. In addition, an 'impaired' score may be assigned in the setting of several errors including movement in one direction of the reciprocal sequence, movement which is less than half of the available passive ROM, or movement which requires a longer time than the three-second verbal count to complete (Fowler et al., 2009). Allowing a 'normal' score to be assigned in the setting of isolated movement within a limited range (e.g. 50% of the passive ROM) offers a mechanism to differentiate between muscle weakness and a lack of SVMC (Cahill-Rowley & Rose, 2014). A score of 'unable' is given when movement is not initiated or occurs in mass synergy (Fowler & Goldberg, 2009).

Several studies have been conducted to investigate the validity and reliability of the SCALE as a clinical measure of SVMC in children with CP. When compared with the Gross Motor Function Classification System (GMFCS), construct validity was demonstrated by a significant inverse correlation (Spearman's $r = -.83$, $p < .001$). The SCALE was also found to have high interrater reliability (intraclass correlation coefficient .88-.91, $p < .001$) (Fowler et al., 2009). Further investigation aimed to correlate the SCALE with other clinical tests, including the Fugl-Meyer Assessment, Manual Muscle Test, and Modified Ashworth Scale, yielded additional evidence to demonstrate the SCALE's construct validity (Balzer et al., 2016). Selective voluntary motor control was considered to be a significant factor influencing gross motor function in individuals with bilateral CP, whereby a strong positive correlation was seen between the Gross Motor Function Measure (GMFM-66) and the SCALE (Spearman's $r = .90$, $p \leq .001$) (Noble et al., 2019).

Another method of assessing SVMC that has been described is the use of surface electromyography (sEMG). Perry identified the presence of an extensor synergy across different muscle groups in pathological gait, observed as coactivation of gluteus medius, vastus lateralis, and soleus muscles during stance phase (Cahill-Rowley & Rose, 2014). Later work investigated differences between obligatory coactivation of the quadriceps and gastrocnemius muscles in children with CP and idiopathic toe walking. Children with CP were found to exhibit greater overlap in activation timing between the muscles during attempted isolated voluntary movement (e.g. isometric activation of knee extensors and resisted knee extension) as compared to those with idiopathic toe walking. No differences in sEMG patterns between the groups were observed during gait (Cahill-Rowley & Rose, 2014; Rose et al., 1999). Zwaan et al. (2012) examined the overlap of activation timing of the vastus medialis, semitendinosus, and gastrocnemius muscles during gait using sEMG in children with CP and typically developing (TD) children (Zwaan et al., 2012). While the findings demonstrated mean differences in sEMG timing during gait between the two groups, there was also considerable overlap. As such, the extensor synergy was not considered a sensitive measure to assess the magnitude of SVMC at an individual level (Cahill-Rowley & Rose, 2014; Zwaan et al., 2012). Earlier assessments of SVMC using sEMG involved isolated joint movements during attempted voluntary tasks instead of during functional activities, such as walking, as it was considered difficult to discern impairments in SVMC from the presence of other neuromuscular constraints. Further, the use of sEMG to assess SVMC requires equipment and expertise to collect, process, and interpret the data (Cahill-Rowley & Rose, 2014).

The use of sEMG during the SCALE testing procedure has been explored in an effort to objectively and more precisely quantify SVMC (Balzer et al., 2022a). A similarity index (SI), proposed by Lee et al. (2004), measures the degree to which an individual's sEMG pattern, or motor control, during a voluntary movement resembles that of a reference group (Lee et al., 2004). The SI is derived using a vector analysis method whereby the average root mean square for each muscle is combined and compared to the reference vector using the scalar product. An SI value closer to one is more similar to the reference group. Preliminary validity and reliability of the SI_{SCALE} was investigated, comparing children with CP to a neurologically intact adult group. Strong correlations between SI_{SCALE} and SCALE scores ($r = .90, p < .001$) as well as GMFCS levels ($r = -.74, p < .001$) were demonstrated, establishing concurrent validity of the

$\mathrm{SI}_{\mathrm{SCALE}}$. Test-retest reliability was determined to be in a moderate to good range. The $\mathrm{SI}_{\mathrm{SCALE}}$ allows for the measurement of SVMC in the setting of significant muscle weakness or decreased joint movement. Analysis of the response vector for a given movement provides additional information about the impaired SVMC, allowing for differentiation between coactivation of muscles of the same limb or mirror activity on the contralateral side. Further work is needed to assess responsiveness to change of the $\mathrm{SI}_{\mathrm{SCALE}}$ (Balzer et al., 2022b).

More recently, muscle synergies have been proposed as a method of quantifying SVMC during walking. Muscle synergies, defined as ‘weighted groups of muscles identified mathematically from sEMG data’, represent ‘coordinated patterns of muscle activity that flexibly combine to produce functional motor behaviors’ (Schwartz et al., 2016). They are considered to reflect a more simplified control strategy as compared to modulating each muscle individually (Schwartz et al., 2016). The Walking Dynamic Motor Control Index (walk-DMC) was developed to quantify the complexity of neuromuscular control during walking (Steele et al., 2015). The walk-DMC is computed from sEMG data using non-negative matrix factorization and is calculated as a z-score, such that 100 is the average for typical development and every 10 points represents one standard deviation (SD) from typical development. A more complex muscle activation pattern during walking is observed as a larger walk-DMC. When compared with unimpaired individuals, those with CP exhibited fewer synergies in their movement patterns. The walk-DMC was found to decrease with more severe diagnosis subtypes, characterized based upon topographic distribution (e.g. hemiplegia, diplegia, triplegia, quadriplegia), as well as with functional impairment, as measured by GMFCS level. The walk-DMC was also compared to other clinical measures, including strength of the hip, knee, and ankle assessed using the Kendall scale ($r = .49$), SVMC of the hip, knee, and ankle described as ‘patterned’, ‘partly isolated’, and ‘completely isolated’ (*r* = .44), and spasticity using the Ashworth Scale (*r* = -.34) (Steele et al., 2015).

While synergy activations and weights have been shown to differ across different GMFCS levels and different topographical distributions, a more recent study sought to determine if synergy structures were different between gait patterns. Children were classified into one of six gait patterns, including drop foot, genu recurvatum, apparent equinus, crouch gait, jump gait, or true equinus. The results revealed that synergy structure was similar amongst the gait patterns, while a high variability was demonstrated between individual participants. The authors concluded that while the central nervous system employs ‘generic movement patterns’ to compensate for brain lesions, children with CP exhibit ‘individualized motor control strategies’ (Goudriaan et al., 2022).

Several studies have been conducted to explore associations between SVMC, as measured by walk-DMC, and treatment outcomes. Schwartz et al. (2016) evaluated whether walk-DMC had a significant effect on changes in gait pattern, gait speed, energy cost of walking, and function after treatment consisting of orthopaedic surgery or selective dorsal rhizotomy (SDR). The findings demonstrated that walk-DMC was significantly associated with gait, measured by the Gait Deviation Index (GDI), speed, and function. The GDI is a measure of overall gait quality (Schwartz & Rozumalski, 2008). Further, those individuals with higher walk-DMC scores, or less impaired SVMC, exhibited greater improvements in walking ability following treatment compared to individuals with more impaired SVMC (Schwartz et al., 2016). Similar findings were observed when walk-DMC and treatment outcomes were explored across clinical centers. Shuman et al. (2019) explored whether muscle synergies change following treatments, including single-event multilevel orthopaedic surgery (SEMLS), selective dorsal rhizotomy (SDR), or botulinum toxin injections. The results did not demonstrate significant changes in the number of synergies for any treatment group, suggesting the potential difficulty in altering SVMC in children with CP (B. R. Shuman et al., 2019). A recent systematic review of existing studies investigating muscle synergies during walking in children with CP suggested that the use of muscle synergies to measure SVMC and predict outcomes seemed promising (Bekius et al., 2020).

While there are several approaches available to assess SVMC, most agree that quantifying motor control is challenging. The SCALE is easy to administer and does not require the use of specialized equipment (Fowler et al., 2009). The testing procedure attempts to differentiate between altered SVMC and deficits in muscle strength, such that an individual can obtain a score of two (normal SVMC) even if they are only able to move the designated limb through 50% of the available passive ROM of the joint. The tool also includes 'descriptors' which can assist in further characterizing impaired SVMC (Balzer et al., 2017a). Unlike other clinical tools described to assess SVMC, the SCALE includes five joints of the lower extremity. Several limitations of the SCALE have been identified. Some have argued that the testing procedure (e.g. extend, flex, extend the knee) involves non-functional movements (Schwartz et al., 2016). The assessment is subjective and it has been suggested that the ordinal scoring system may lack the sensitivity necessary to measure small changes in SVMC (Balzer et al., 2017a). On the contrary, the use of muscle synergies to measure SVMC has been thought to provide a more objective assessment during the functional task of walking. That said, synergy analysis requires the use of sEMG, which can be more time- and cost-intensive and not as readily available in clinical settings (Bekius et al., 2020). Furthermore, altered muscle activation during walking in the setting of musculoskeletal impairments is important to recognize. For example, a child walking with crouch (e.g. increased hip and knee flexion and ankle dorsiflexion) may exhibit continuous co-activation of the lower extremity musculature as a result of the biomechanical constraints associated with gait pattern.

1.2 Influence of Impaired Selective Voluntary Motor Control on Gait in Children with Cerebral Palsy

Several studies have sought to explore the relationship between impaired SVMC on gait in children with CP. Chruscikowski et al. (2017) found a positive relationship between SVMC, as measured by the SCALE, and the Gait Profile Score (GPS) (Chruscikowski et al., 2017). The GPS is based upon lower limb parameters associated with typical gait pathologies in children with CP and represents the root mean square difference between the individual's joint kinematic curve and the mean normative curve (Dussault-Picard et al., 2022). Significant differences in SCALE scores across GMFCS levels I, II, and III were also found (Chruscikowski et al., 2017). Sardogan et al. (2021) explored the relationship between SVMC and gait pathology, as measured by the Edinburgh Visual Gait Score (EVGS), an observational gait assessment tool. The results demonstrated a relationship between SVMC, as measured by the SCALE, and ankle and foot movements during swing phase (Sardoğan et al., 2021). Zhou et al. (2019) explored the influence of impaired SVMC, as measured by the SCALE, on temporal-distance parameters and kinematics in children with CP. A significant association between impaired SVMC and increased knee flexion at initial contact, decreased step lengths, and decreased gait speed was found. Impaired SVMC was not associated with the mid-stance phase of the gait cycle, during which time the hip and knee are extending simultaneously (Zhou et al., 2019).

Adequate step length and pre-positioning of the lower limb during terminal swing phase are two important prerequisites of normal gait (Gage, 1993). Reduced step lengths can impact overall walking velocity. A common goal amongst children with CP and their caregivers is the ability to walk and keep up with their peers. Selective voluntary motor control is considered to be important during terminal swing phase, whereby the hip joint is flexing with concomitant extension of the knee joint. As such, research has focused on the influence of impaired SVMC during terminal swing phase and at initial contact. Fowler et al. (2009) explored interjoint coordination of the hip and knee joints using relative phase analysis. They found that children with CP exhibited a shorter duration of uncoupled hip and knee movement (e.g. less coordinated) during swing phase in comparison to a TD group (Fowler & Goldberg, 2009). Dussault-Piccard et al. (2022) also utilized continuous relative phase analysis to explore coordination of the hip and knee joints as well as the knee and ankle joints. Similar to the earlier findings by Fowler et al. (2009), the authors found a less coordinated pattern of movement in those with CP. Interestingly, they observed this decreased coordination at more challenging transitional periods of the gait cycle, namely during terminal swing phase and initial contact (Dussault-Picard et al., 2022).

More recently, Daly (2021) sought to explore the factors associated with terminal swing phase knee flexion, which is commonly observed in individuals with CP. The findings from this study demonstrated that the degree of knee flexion during the stride, the velocity of knee extension, hamstring lengthening characteristics via computational modelling techniques, and GMFCS were associated with increased knee flexion during terminal swing. Gait speed and clinical measures of hamstring length were not found to be associated with increased knee flexion during terminal swing phase. The role of SVMC as a potential factor was not included. A limitation of this study, as recognized by the author, was the challenge in isolating the influence of a single factor in the setting of multicollinearity amongst the factors (Daly, 2021).

Causal inference modelling has been employed to better understand the influence of specific impairments on aspects of function, recognizing the shortcomings of assumed 'causation by association' with multiple linear regression approaches, especially amidst the heterogeneity associated with CP (MacWilliams et al., 2022). For example, decreased knee extension during terminal swing phase may be associated with decreased strength of the knee extensors. However, impaired SVMC may also impede knee extensor strength. Gill et al. (2023) explored the causal factors associated with metabolic energy in CP. Results from this work revealed that gait, as measured by the GDI, and SVMC, as measured by a clinical tool other than the SCALE as well as by the walk-DMC, had the largest effect on metabolic power. Interestingly, muscle strength demonstrated the smallest effect (Gill et al., 2023). Steele et al. (2022) used causal modelling to explore the influence of impaired SVMC, as measured by the walk-DMC, on outcomes, as measured by the GDI, following SEMLS in CP. Walk-DMC was found to be related to the pre-operative GDI, however, a small effect of walk-DMC on changes in GDI following intervention were observed. It is important to note that, in general, SEMLS had a small effect on changes in GDI. Conclusions from this study suggest that there are other factors (e.g. post-operative rehabilitation, surgeon skill, etiology of CP) that have not been explored when assessing the outcomes of intervention on gait in children with CP (Steele & Schwartz, 2022).

Improving the ability to walk remains an important treatment objective amongst clinicians and a meaningful goal for children with CP and their caregivers. Gait pathology in children with CP is the result of a complex interaction of musculoskeletal and neuromuscular impairments. Research has demonstrated that impaired SVMC contributes to gait dysfunction in children with CP and, in some cases, may play a greater role than other impairments, such as spasticity or muscle weakness. A better understanding of the factors associated with gait impairment will likely result in improved outcomes and aid in avoiding those interventions which can lead to iatrogenic gait deviations in this population.

Chapter 2: Assessment of Selective Voluntary Motor Control in Ambulatory Children with Cerebral Palsy

2.1 Background

Children with cerebral palsy (CP) demonstrate limitations in selective voluntary motor control (SVMC), among other impairments, such as hypertonia, muscle weakness, and joint contractures (Balzer et al., 2017a). The United States National Institutes of Health Pediatric Motor Disorders Taskforce defined SVMC as the ability to isolate the activation of muscles in a selected pattern in response to the demands of a voluntary movement or posture (Sanger et al., 2006). The findings from several research studies have suggested that reduced SVMC contributes more to impaired motor performance than other factors, such as hypertonia or contractures (Balzer et al., 2017b). Clinicians and researchers alike agree that SVMC is an important prognostic factor of functional ability as well as of outcomes following interventions for individuals with CP (Fowler & Goldberg, 2009). Appropriate assessment methods are critical to further understand the influence of impaired SVMC on function in children with CP (Sardoğan et al., 2021).

A variety of clinical assessments have been described to examine SVMC of the lower extremities in children with CP. The methods of assessment vary in relation to the joints tested, the positions used, the actions or tasks performed, and the mechanisms for scoring (Fowler & Goldberg, 2009). The Selective Control Assessment of the Lower Extremity (SCALE) was developed as an objective clinical assessment method of SVMC in children with CP. The tool can be administered in less than fifteen minutes and does not require specialized equipment. The testing procedure involves the assessment of a reciprocal movement which does not involve mass flexion or extension for each of five joints of both lower extremities. A score of ‘normal’ (two points), ‘impaired’ (one point), or ‘unable’ (zero points) is given to each joint and total limb scores for both lower extremities are summated. A score of ‘normal’ SVMC for a given joint is given when the reciprocal movement pattern is performed within a defined verbal cadence without concomitant movement observed at joints of the test limb or the contralateral side. A score of ‘impaired’ SVMC is given when isolated movement is only observed for part of the sequence. In addition, an ‘impaired’ score may be assigned in the setting of several errors including movement in one direction of the reciprocal sequence, movement which is less than half of the available passive range of motion (ROM), or movement which requires a longer time than the three-second verbal count to complete (Fowler et al., 2009). Allowing a ‘normal’ score to be assigned in the setting of isolated movement within a limited range (e.g. 50% of the passive ROM) offers a mechanism to differentiate between muscle weakness and a lack of SVMC (Balzer et al., 2016). A score of ‘unable’ is given when movement is not initiated or occurs in mass synergy (Fowler et al., 2009).

More recently, muscle synergies have been proposed as a method of quantifying SVMC during walking (Schwartz et al., 2016; B. Shuman et al., 2016). Muscle synergies, defined as weighted groups of muscles identified mathematically from surface electromyography (sEMG) data, represent ‘coordinated patterns of muscle activity that flexibly combine to produce functional motor behaviors’ (Schwartz et al., 2016; B. Shuman et al., 2016). They are considered to reflect a more simplified control strategy as compared to modulating each muscle individually (Schwartz et al., 2016). The Walking Dynamic Motor Control Index (walk-DMC) was developed to quantify the complexity of neuromuscular control during walking. Non-negative matrix factorization is used to derive the synergy structure from sEMG data. The total variance accounted for by one synergy (VAF_1) is then computed. The walk-DMC is calculated as a z-score, such that 100 is the average for typical development (TD) and every 10 points represents one standard deviation (SD) from TD (Steele et al., 2015) (Figure 1). A more complex muscle activation pattern during walking is observed as a larger walk-DMC score (Schwartz et al., 2016).

$$\text{Walk-DMC} = 100 + 10\left[\frac{(1-\text{VAF}_1) - (1-\text{VAF}_1)_{\text{TD\_AVE}}}{(1-\text{VAF}_1)_{\text{TD\_SD}}}\right]$$

Figure 1: Walk-DMC computed by determining the total variance in sEMG accounted for by one synergy, then transforming one minus this variance to a z-score with respect to children with typical development (TD), where $(1\text{-}VAF_1)$ is the variance not accounted for by one synergy in a given individual, and $(1\text{-}VAF_1)_{TD\_AVE}$ and $(1\text{-}VAF_1)_{TD\_SD}$ are the average (AVE) and standard deviations (SD) of the unaccounted variance in children with TD.

When compared with unimpaired individuals, those with CP have been shown to exhibit fewer synergies in their movement patterns (Schwartz et al., 2016). The walk-DMC has been found to decrease with more severe diagnosis subtypes, characterized based upon topographic distribution (e.g. hemiplegia, diplegia, triplegia, quadriplegia), as well as with functional impairment, as measured by the Gross Motor Function Classification System (GMFCS). The walk-DMC has also been compared to other clinical measures, including strength of the hip, knee, and ankle musculature assessed using the Kendall scale, SVMC of the hip, knee, and ankle described as ‘patterned’, ‘partly isolated’, and ‘completely isolated’, and spasticity using the Ashworth Scale (Steele et al., 2015). To the knowledge of the authors, the walk-DMC has not been directly compared to the SCALE. Therefore, the aim of this study was to further evaluate the concurrent validity of the walk-DMC as a measure of SVMC in children with CP. It was hypothesized that walk-DMC scores would be positively correlated with SCALE scores.

2.2 Methods

Study Population

This IRB-approved study involved a retrospective analysis of instrumented gait data, inclusive of sEMG, from an accredited motion analysis laboratory from January of 2015 to December of 2021. Participants between the ages of 5-17 years with a diagnosis of CP, GMFCS levels I, II, and III were included. Individuals with a history of prior surgeries were not excluded.

Data Collection

Surface EMG data from four muscles (rectus femoris, medial hamstrings, tibialis anterior, and gastrocnemius) were processed in accordance with routine clinical protocols and were averaged over a minimum of five barefoot gait cycles. The synergy structure from the averaged EMG signals was derived using non-negative matrix factorization in MATLAB®. The total VAF_1 for each individual was computed for the more impaired limb, as determined by the Gait Deviation Index (GDI), for individuals with diplegia, or for the more affected side for those with hemiplegia or triplegia. The walk-DMC was then calculated using the average (.758) and SD (.07) of the total VAF_1 for 84 individuals without impairment, as reported in the literature (Steele et al., 2015). This was done in the absence of a sEMG database for TD individuals in our laboratory. The SCALE was administered according to testing procedure and the total limb score for the respective side was used for comparison with the walk-DMC scores.

Data Analysis

The assumption of homogeneity of variances was assessed using Levene's test for equality of variances. The assumption of normality was assessed using the Shapiro-Wilk test for normality. A one-way analysis of variance (ANOVA) was used to compare walk-DMC scores across GMFCS levels with a least significant difference (LSD) post-hoc analysis for comparisons between groups. A Pearson's correlation was used to investigate the relationship between SCALE and walk-DMC scores. All statistical analyses were conducted in SPSS® and significance was set at $p \leq .05$ for all tests.

2.3 Results

Participant characteristics are summarized in Table 1. The inclusion and exclusion criteria resulted in 50 individuals with CP (GMFCS level I, $n = 18$; GMFCS level II, $n = 16$; GMFCS level III, $n = 16$). A subset of 35 individuals (GMFCS level I, $n = 16$; GMFCS level II, $n = 12$; GMFCS level III, $n = 7$) for whom the SCALE was administered by a single evaluator, was used for the comparison of walk-DMC and SCALE scores.

Table 1: Participant Characteristics

	$n = 50$
Age (years): mean (SD)	10.48 (3.0)
Sex: female (male)	19 (31)
GMFCS Level	
GMFCS I	18
GMFCS II	16
GMFCS III	16

The assumption of homogeneity of variances was not violated, as assessed by Levene's test for equality of variances ($p = .089$). Data was normally distributed for each group, as assessed by the Shapiro-Wilk test ($P > .05$). The one-way ANOVA was used to determine if walk-DMC scores were different across GMFCS levels. The walk-DMC score was statistically different between groups, $F(2, 47) = 10.424$, $p < .001$, with decreased walk-DMC scores observed with increasing functional impairment (Figure 2). Walk-DMC scores decreased from GMFCS I ($M = 88.86$, $SD = 8.2$) to GMFCS II ($M = 83.30$, $SD = 86.9$) and to GMFCS III ($M = 78.08$, $SD = 8.1$). The LSD post-hoc analysis revealed a statistically significant mean difference in walk-DMC scores between GMFCS level I and II (5.56, 95% CI [.805, 10.315], *p* = .023), II and III (5.22, 95% CI [.325, 10.110], *p* = .037), and I and III (10.78, 95% CI [6.023, 15.532], *p* = .000).

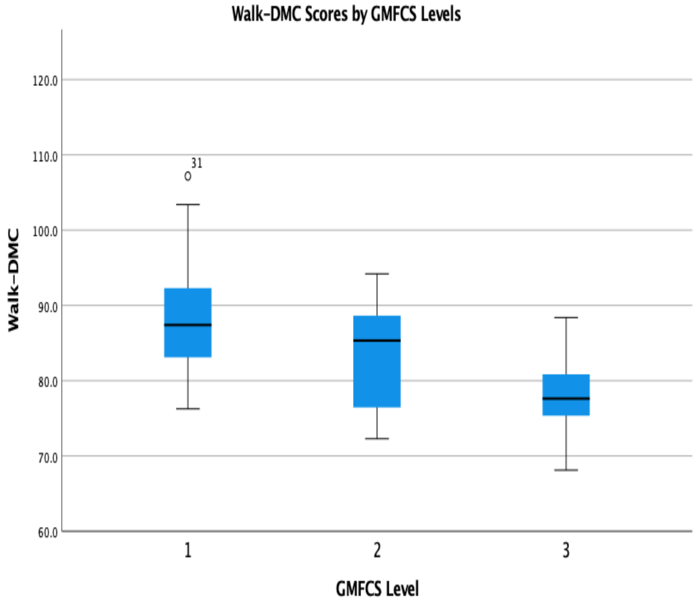

Figure 2: One-way ANOVA used to compare walk-DMC scores across GMFCS levels. Significant difference observed across all three groups (*p* < 0.0001), with decreased walk-DMC scores observed with increasing functional impairment.

A Pearson's correlation was used to investigate the relationship between SCALE and walk-DMC scores in a subset for whom the SCALE was administered by a single evaluator. There was a statistically significant, strong positive correlation between SCALE and walk-DMC, *r*(33) = .64, *p* < .001, with SCALE scores explaining 41% of the variation in walk-DMC scores (Figure 3).

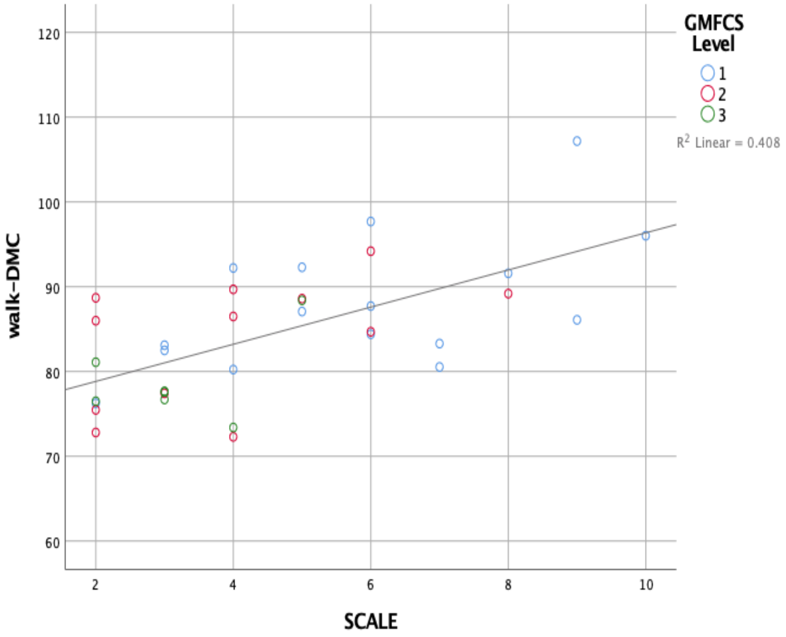

Figure 3: Pearson's correlation used to investigate relationship between walk-DMC and SCALE scores, (*r* = .64, *p* < .001).

2.4 Discussion

Several studies have sought to explore the relationship between impaired SVMC on gait in children with CP. Chruscikowski et al. (2017) found a positive relationship between SVMC, as measured by the SCALE, and the Gait Profile Score (GPS), a summary index of gait pathology associated with kinematic variables. Significant differences in SCALE scores across GMFCS levels I, II, and III were also reported (Chruscikowski et al., 2017). Sardogan et al. (2021) explored the relationship between SVMC and gait pathology, as measured by the Edinburgh Visual Gait Score (EVGS), an observational gait assessment tool. The results demonstrated a relationship between SVMC, as measured by the SCALE, and ankle and foot movements during swing phase (Sardoğan et al., 2021). Goudriaan et al. (2022) investigated the influence of impaired SVMC, as measured by muscle synergies, on different gait patterns (e.g. crouch, jump gait, equinus). Contrary to their hypothesis, the authors found a similar synergy structure between the various gait patterns. They did observe a high variability in muscle synergies across individuals. The authors concluded that while a generic motor control strategy may be employed in the setting of the brain injury, individual differences do exist (Goudriaan et al., 2022). Sorek at el. (2023) found minimal mean changes in SVMC, as measured by the walk-DMC, and gait, as measured by the GPS, on two different instrumented gait analysis (IGA) visits, with no intervention in between. Similar to the study by Goudriaan et al. (2022), the results from this study reported variability in walk-DMC between individuals. The observed changes in walk-DMC were associated with changes in kinematics at the hip in the sagittal and transverse planes (Sorek et al., 2023).

Clinicians and researchers alike agree that SVMC is an important consideration when proposing treatment recommendations to improve function in children with CP. Schwartz et al. (2016) and Shuman et al. (2018) demonstrated that those with less impaired SVMC, as measured by the walk-DMC, exhibited improved outcomes by way of gait speed, function, and overall gait pathology, as measured by the GDI (Schwartz et al., 2016; B. R. Shuman et al., 2018). These findings suggest that SVMC plays a prognostic role in determining if a child is an ideal candidate for a certain intervention to improve their walking ability. Moreover, researchers have suggested that efforts be directed toward exploring treatments that may improve SVMC. Shuman et al. (2019) found minimal changes in synergy structure following treatment, despite observed improvements in gait, suggesting that SVMC cannot be altered following interventions targeted at the musculoskeletal system (B. R. Shuman et al., 2019). One aim of the systematic review conducted by Balzer et al. (2017) was to determine the trainability of SVMC. Conclusions from this work highlighted the ongoing need to first improve assessment methods of SVMC (Balzer et al., 2017a).

While the primary aim of this study was to further explore validity of the walk-DMC as a measure of SVMC, a preliminary step was to examine walk-DMC scores across GMFCS levels using the mean and SD for VAF_1 as reported in the literature, in the absence of a database of sEMG data for TD individuals. When employing this novel approach, we found that walk-DMC scores were significantly different across GMFCS levels I, II, and III and that decreased SVMC (e.g. lower walk-DMC scores) was observed in those individuals with greater functional impairment (e.g. GMFCS level III). This finding is consistent with Steele et al. (2015), whereby decreased walk-DMC scores were observed with increasing functional impairment (Steele et al., 2015). While walk-DMC scores were significantly different across GMFCs levels, there was a certain degree of spread and overlap observed, similar to that seen by Steele et al. (2015), which is thought to represent the heterogeneous nature of CP (Steele et al., 2015). These findings are promising for other laboratories without a sEMG database for TD individuals, who are interested in incorporating synergy analysis as part of their clinical gait analysis standard of care. MacWilliams et al. (2021) recently demonstrated that walk-DMC scores for TD individuals were comparable across three different centers when similar processing methods were used. While it remains best practice to utilize TD data collected locally, the authors concluded that gait laboratories should be able to implement the walk-DMC using the mean and SD for the VAF_1 of the TD group as well as the exact processing protocol described in their study (MacWilliams et al., 2021).

The purpose of this study was to further establish concurrent validity of the walk-DMC by comparing it to the SCALE, which has been established as a valid and reliable clinical measure of SVMC in children with CP (Balzer et al., 2016; Fowler et al., 2009). The associated results demonstrated a strong positive correlation between the walk-DMC and the SCALE, offering further support for synergy analysis as a measure of SVMC in this population. These findings are consistent with results from Steele et al. (2015), who demonstrated that walk-DMC scores correlated with various clinical examination measures, including strength (*r* = .49), spasticity (*r* = -.34), and selective motor control (*r* = .44) in a group of 549 individuals with CP (Steele et al., 2015).

A variety of clinical assessments have been described to examine SVMC of the lower extremities in children with CP, each with strengths and limitations. The SCALE is easy to administer and does not require the use of specialized equipment (Fowler et al., 2009). The testing procedure attempts to differentiate between altered SVMC and deficits in muscle strength and the tool includes 'descriptors' which can assist in further characterizing impaired SVMC (Balzer et al., 2016). Unlike other clinical tools described to assess SVMC, the SCALE includes five joints of the lower extremity. Several limitations of the SCALE have been identified. Some authors argue that the testing procedure (e.g. extend, flex, extend the knee) involves non-functional movements (Schwartz et al., 2016). The assessment is subjective and the ordinal scoring system may lack the sensitivity necessary to measure small changes in SVMC (Balzer et al., 2017a). On the contrary, the use of muscle synergies to measure SVMC has been thought to provide a more objective assessment during the functional task of walking (Schwartz et al., 2016). However, synergy analysis requires the use of sEMG, which can be more time- and cost-intensive and not as readily available in clinical settings (Bekius et al., 2020). Furthermore, altered muscle activation during walking can be a manifestation of certain musculoskeletal impairments. For example, a child walking with a crouch gait pattern (e.g. increased hip and knee flexion and ankle dorsiflexion) may exhibit continuous co-activation of the lower extremity musculature as a result of the biomechanical constraints inherent to the observed gait pattern.

There are several recognized limitations of this study. First, the study design was retrospective. A second limitation of the study was the absence of a normative sEMG database, necessitating use of the reported mean and SD for VAF_1 in a TD group when calculating walk-DMC scores. Finally, the influence of walking speed on walk-DMC was not explored in this study.

In conclusion, individuals with CP exhibit deficits in SVMC, which have been demonstrated to contribute to impaired gross motor function. Improved outcomes following a variety of treatments are associated with less impaired SVMC. Quantifying motor control is challenging, however, there are several approaches available to assess SVMC in individuals with CP. The recent use of muscle synergy analysis offers an objective method to measure SVMC during the functional task of walking in this population. Nevertheless, an individualized approach to ascertaining the influence of impaired SVMC on gross motor function, and in particular on walking, is warranted in a heterogeneous condition such as CP.

Chapter 3: The Influence of Selective Voluntary Motor Control on Terminal Swing Phase in Ambulatory Children with Cerebral Palsy

3.1 Background

The acquisition and maintenance of the ability to walk and keep up with peers is an important goal amongst children with cerebral palsy (CP) and their caregivers. As such, factors associated with decreased walking speed are of interest amongst clinicians and researchers. Gait pathology in this population is complex. Gait deviations can be characterized as primary (e.g. produced directly by the neurological injury, such as spasticity), secondary (e.g. occur as a result of abnormal growth and development of the musculoskeletal system, such as lever arm dysfunction), and tertiary (e.g. compensatory or coping responses) (Gage, 1993). Discerning the individual contributions to gait deviations amongst the myriad of impairments associated with CP can be challenging. In some cases, interventions are undertaken to target the tertiary manifestations without an understanding of or an appreciation for the primary and secondary causes of the gait pathology. Moreover, the outcomes following intervention to improve the walking ability of children with CP have been shown to be highly variable. To this end, there is a need to identify patient-specific characteristics which guide decision-making around potential treatment options and assist in predicting outcomes (Schwartz et al., 2016).

Selective voluntary motor control (SVMC) is one of many impairments that is related to gait pathology in individuals with CP. By definition, SVMC refers to the ability to activate the muscles in a selected pattern in response to the demands of a voluntary movement or posture (Sanger et al., 2006). The findings from several research studies have suggested that reduced SVMC contributes more to impaired motor performance than other factors, such as hypertonia or contractures (Balzer et al., 2017b). Quantifying motor control is challenging, however, there are several approaches available to assess SVMC in individuals with CP. The Selective Control Assessment of the Lower Extremity (SCALE) was developed as an objective clinical assessment method of SVMC in children with CP (Fowler et al., 2009). The SCALE is easy to administer and does not require the use of specialized equipment (Fowler et al., 2009). Some have noted that the testing procedure involves non-functional movements, the assessment is subjective, and the ordinal scoring system may lack the sensitivity necessary to measure small changes in SVMC (Balzer et al., 2017a; Schwartz et al., 2016). More recently, the use of muscle synergy analysis has been proposed as an objective method to measure SVMC. The Walking Dynamic Motor Control Index (walk-DMC) was developed to quantify the complexity of neuromuscular control during walking (Steele et al., 2015). The walk-DMC is calculated as a z-score, such that 100 is the average for typical development (TD) and every 10 points represents one standard deviation (SD) from TD (Steele et al., 2015). A more complex muscle activation pattern during walking is observed as a larger walk-DMC score (Schwartz et al., 2016). We found the walk-DMC to have a strong positive correlation with the SCALE ($r = .64$, $p \leq .001$), offering further support for synergy analysis as a measure of SVMC in this population.

Impaired SVMC manifests in several different ways in children with CP. Alterations in the speed of movement or the presence of mirror movements, observed as simultaneous associated movements at contralateral joints, are often seen upon clinical examination of SVMC (Fowler et al., 2009). The inability to activate an individual muscle group without concomitant activity of the antagonist musculature can result in errors of the timing of muscle recruitment during a given movement. Children with CP who exhibit impaired SVMC can have difficulty moving the hip, knee, and ankle joints independently of one another, which can be observed as mass patterns of flexion or extension (Fowler & Goldberg, 2009).

Prior research has focused upon the influence of impaired SVMC on gait in children with CP. Chruscikowski et al. (2017) found a positive relationship between SVMC, as measured by the SCALE, and the Gait Profile Score (GPS) (Chruscikowski et al., 2017). The GPS is based upon lower limb parameters associated with typical gait pathologies in children with CP and represents the root mean square difference between the individual's joint kinematic curve and the mean normative curve (Dussault-Picard et al., 2022). Significant differences in SCALE scores across Gross Motor Function Classification System (GMFCS) levels I, II, and III were also observed (Chruscikowski et al., 2017). Sardogan et al. (2021) explored the relationship between SVMC and gait pathology, as measured by the Edinburgh Visual Gait Score (EVGS), an observational gait assessment tool. The results demonstrated a relationship between SVMC, as measured by the SCALE, and ankle and foot movements during swing phase (Sardoğan et al., 2021).

Adequate step length and pre-positioning of the lower limb during swing phase, each prerequisites of normal gait, are directly related to walking speed. Decreased knee extension during the terminal swing phase of gait is one of a variety of factors that contributes to inadequate step length (Arnold et al., 2007). Children with CP commonly exhibit deficits in knee extension at terminal swing phase (Fowler & Goldberg, 2009). Reduced hamstring length and the presence of hamstring spasticity have been attributed to decreased knee extension during terminal swing phase, as a result of which, hamstring lengthening surgery has been proposed to improve knee extension during gait (Daly, 2021; Fowler & Goldberg, 2009; Zhou et al., 2019). The findings from prior research, however, suggest that decreased knee extension in terminal swing phase is multifactorial, and that hamstring lengthening procedures should be indicated with caution (Daly, 2021). Improvements following hamstring surgery are not consistent and terminal swing phase knee extension following intervention has not been shown to approach normative values (Fowler & Goldberg, 2009). Moreover, iatrogenic gait deviations, such as an increased anterior pelvic tilt and knee hyperextension, have been observed following hamstring lengthening surgery (de Morais Filho et al., 2020).

Intact SVMC is considered to be essential during terminal swing phase, whereby hip flexion, knee extension, and ankle dorsiflexion occur concomitantly (Cahill-Rowley & Rose, 2014; Dussault-Picard et al., 2022; Fowler et al., 2009; Fowler & Goldberg, 2009; Zhou et al., 2019). Several studies have explored the influence of impaired SVMC on terminal swing phase and initial contact. Fowler et al. (2009) explored interjoint coordination of the hip and knee joints using relative phase analysis and found that children with CP exhibited a shorter duration of uncoupled hip and knee movement (e.g. less coordinated) during swing phase in comparison to a TD group (Fowler & Goldberg, 2009). Dussault-Piccard et al. (2022) also utilized continuous relative phase analysis to explore coordination of the hip and knee joints as well as the knee and ankle joints. Similar to the earlier findings by Fowler et al. (2009), the authors found a less coordinated pattern of movement in those with CP. Interestingly, the decreased coordination was observed at more challenging transitional periods of the gait cycle, namely during terminal swing phase and at initial contact (Dussault-Picard et al., 2022).

Zhou et al. (2019) explored the influence of impaired SVMC, as measured by the SCALE, on temporal-distance parameters and kinematics. A significant association was found between impaired SVMC and increased knee flexion at initial contact, reduced step lengths, and reduced gait speed. Impaired SVMC was not associated with mid-stance phase of the gait cycle, during which time the hip and knee are extending simultaneously (Zhou et al., 2019). More recently, Daly (2021) sought to explore factors associated with increased terminal swing phase knee flexion. Contrary to the findings by Zhou et al. (2019), gait speed was not found to be associated with increased knee flexion during terminal swing phase. The degree of knee flexion during the stride, the velocity of knee extension, hamstring lengthening characteristics via musculoskeletal modelling techniques, and GMFCS level were associated with increased knee flexion during terminal swing, while clinical measures of hamstring length, as measured by the popliteal angle, were not associated (Daly, 2021).

While many, though not all, of the prior studies incorporated a measure of SVMC, including the SCALE or interjoint coordination using the relative phase method, none have employed a task-specific measure of motor control, such as the walk-DMC, when exploring the influence of impaired SVMC on the terminal swing phase of gait. The primary aim of this study, therefore, was to examine factors associated with the magnitude and timing of knee extension during terminal swing phase, including a task-specific measure of SVMC, in a group of children with diplegia. The predictors of interest included SVMC, knee and ankle joint range of motion (ROM), hamstring muscle spasticity, measures of knee extensor strength, and hamstring muscle-tendon lengthening characteristics of the swing limb, as well as stability of the contralateral limb during stance phase. It was hypothesized that impaired SVMC of the swing limb, as measured by walk-DMC, and decreased stance phase stability, as measured by single limb support time of the stance limb, would be significant predictors of a decreased magnitude of knee extension during terminal swing phase. The secondary aim of this study was to examine the same relationship in a group of children with hemiplegia, whereby stability in stance phase of the uninvolved limb was less impaired. It was hypothesized that impaired SVMC of the swing limb in the group with hemiplegia would be a significant predictor of decreased knee extension during terminal swing phase.

3.2 Methods

Study Population

This study involved a retrospective analysis of instrumented gait data, inclusive of surface electromyography (sEMG), from an accredited motion analysis laboratory between 2015 and 2024. Participants between the ages of 7-18 years with a diagnosis of diplegic or hemiplegic CP, GMFCS levels I and II were included. Individuals with a history of prior surgeries were not excluded in an effort to provide a representative sample of individuals with CP who were referred for gait analysis. For participants with multiple gait analysis visits, we selected the initial visit to include those who were treatment naïve. For individuals with diplegia, the more impaired limb, as determined by the Gait Deviation Index (GDI), was used for analysis of the independent variables associated with the swing limb. The GDI is a measure of overall gait pathology. For individuals with hemiplegia, the involved side was selected as the swing limb.

Data Collection

Measures of joint ROM, spasticity, and strength were obtained from the clinical examination conducted at the time of the visit in the motion analysis laboratory. Knee extension and ankle dorsiflexion ROM (°) were assessed in the prone position. A positive value (°) of knee extension ROM denotes hyperextension and a negative value (°) is indicative of the presence of a contracture. Similarly, a negative value (°) of ankle dorsiflexion ROM represents an equinus contracture. The Modified Ashworth Scale (0-4 scale) was used to assess spasticity of the hamstring muscles. Strength of the knee extensors was assessed using the Kendall scale (0-5 scale), as well as the presence or absence of an extensor lag of the knee joint in the supine position.

Kinematic data were collected using a 14-camera motion capture system (Kestrel 4200 cameras and Cortex 8.1 software, Motion Analysis Corp, Rohnert Park, CA, USA) with a modified Cleveland Clinic marker set. Kinematic data were sampled at 100 hertz (Hz). Surface EMG data were sampled at 5000 Hz. Individuals walked barefoot at a self-selected walking speed and data from a minimum of five walking trials were analyzed using Orthotrak 6.6 (Motion Analysis Corp, Rohnert Park, CA, USA). All data were normalized to 100% of the gait cycle. Single limb support time of the stance limb (% of the entire gait cycle), as defined by ipsilateral heel strike to contralateral heel strike, was obtained from the temporal distance parameters. The absolute measures of peak knee extension during terminal swing phase (°), as well as the timing at which the peak knee extension occurred (% of the entire gait cycle), were extracted from the kinematic data for each walking cycle and then averaged.

Selective voluntary motor control was assessed using the walk-DMC (z-score), which was calculated from sEMG data collected during the instrumented gait analysis (IGA), as described by MacWilliams et al. (2021) (MacWilliams et al., 2021). The sequential signal processing steps of the raw data were as follows:

1) **High pass filter**: 4th order zero lag Butterworth high pass 35 hertz (Hz) filter was applied
2) **60 Hz noise assessment and filter**: power in the bandwidth between 59-61 Hz in each channel was calculated
    a. If the bandwidth power was >10% of the entire signal power, a 4th order zero lag Butterworth notch filters for both the 59-61 Hz range and the 119- 121 Hz range were applied
3) **Demean**: signals were adjusted to give a zero mean value

4) **Rectify**: full wave rectification to the signals was applied
5) **Low pass filter**: 4th order zero lag Butterworth low pass 10 Hz filter was applied
6) **Trim**: the first and last 10% of the signal was truncated to remove filter end effects and periods of transient gait
7) **Normalize**: each channel was divided by the maximum value of that channel and sparsely occurring negative values were set to zero
8) **Concatenate**: all included trials were spliced together to create a single array encompassing many strides

The total variance accounted for by one synergy (VAF_1) for each participant was computed, then scaled into a transformed *z*-score using normative values for VAF_1^{AVE} (.6696) and VAF_1^{SD} (.0450), as reported in the literature (MacWilliams et al., 2021). This was done in the absence of a sEMG database for typically developing (TD) individuals in our laboratory.

Musculoskeletal modelling, as described by Kainz and Schwartz (2021), was used to estimate muscle-tendon length (meters) of the hamstring muscles (semimembranosus, semitendinosus, and biceps femoris, long and short heads) during gait (Kainz & Schwartz, 2021). A standard musculoskeletal modelling approach involves scaling a generic musculoskeletal model to the anthropometry of the individual, calculating joint angles using inverse kinematics, and extracting muscle-tendon lengths. In the current study, joint angles were estimated via inverse kinematics in Visual3D 2021, x64 based upon the marker trajectories collected during the IGA. An unscaled, modified OpenSim musculoskeletal model (modif-OSM-CGM-angles), driven by the joint angles created in Visual3D, was then used to calculate muscle-tendon lengths. All muscle-tendon lengths associated with the peak magnitude of knee extension at terminal swing phase were normalized to the maximum hamstring muscle-tendon length during the gait cycle. The normalized muscle-tendon length for the semitendinosus muscle was selected for the analysis.

Data Analysis

Relevant participant characteristics were summarized with descriptive statistics. The assumption of linearity between the dependent variable and the independent variables, both individually and collectively, was assessed using partial regression plots and a plot of studentized residuals against the predicted values, respectively. The assumption of independence of residuals was assessed using the Durbin-Watson statistic. Homoscedasticity was assessed with a visual inspection of a plot of studentized residuals versus unstandardized predicted values. All data were assessed for multicollinearity (correlations of the independent variables greater than .7 and Tolerance values less than .1) through a visual inspection of correlation coefficients and tolerance/Variation Inflation Factor (VIF) values. The data were assessed for possible outliers (standardized residuals greater than ± three SD), high leverage points (leverage values greater than .2) and highly influential points (Cook's Distance values above one). Finally, the assumption of normality of the residuals for multiple regression was assessed using a histogram with a superimposed normal curve as well as a P-P Plot. Additionally, all data were assessed for normality of distribution using the Kolmogorov-Smirnov tests.

Associations between the predictor variables and the magnitude of peak knee extension in terminal swing phase were assessed using correlation analysis, with Pearson’s correlation used for continuous data and Spearman’s rank correlation used for categorical data.

For the primary aim, a forward stepwise multiple linear regression model was used to explore the ability of the independent variables to predict the magnitude and the timing of knee extension during terminal swing phase. Independent variables of interest included SVMC, as measured by walk-DMC, knee extension and ankle dorsiflexion joint ROM, hamstring muscle spasticity, measures of knee extensor strength, and hamstring muscle-tendon lengthening characteristics of the swing limb, as well as single limb support time of the stance limb. Starting with a constant model, terms were added ($p < .05$) in accordance with the proposed hypothesis, whereby the first selected predictor was SVMC of the swing limb, as measured by the walk-DMC, followed by stance phase stability of the contralateral limb, as measured by single limb support time of the stance limb. The final model included those independent variables which did not demonstrate multicollinearity and exhibited the highest ability to predict the magnitude of knee extension in terminal swing phase. Gross Motor Function Classification System level and history of prior surgery were included as covariates. For the secondary aim, the same analysis in a group of individuals with hemiplegia was conducted. All statistical analyses were conducted in SPSS® and significance was set at $p \leq .05$ for all tests.

3.3 Results

Participant characteristics are summarized in Table 1. The initial query associated with the defined inclusion and exclusion criteria yielded 253 individuals. Participants with missing data were removed ($n = 49$). Those participants with a negative value of the averaged peak knee extension magnitude, denoting hyperextension at terminal swing phase, were excluded from the analysis ($n = 9$). Statistical outliers were removed in accordance with studentized deleted residuals greater than ± three SD ($n = 1$), leverage values greater than 0.2 ($n = 10$), and values for Cook's distance above one ($n = 0$).

Table 1: Participant Characteristics

	Diplegia *n* = 90	Hemiplegia *n* = 105
Age (years): mean (SD)	11.21 (2.9)	11.25 (2.9)
Sex: female (male)	38 (52)	38 (67)
Height (cm): mean (SD)	144.00 (17.0)	145.69 (16.0)
Weight (kg): mean (SD)	40.63 (14.9)	42.13 (16.0)
GMFCS level I (n)	35	59
GMFCS level II (n)	55	46
History of prior surgery: no (yes)	48 (42)	70 (35)
Presence of hamstring spasticity: no (yes)	64 (26)	76 (29)
Deficit of knee extensor strength: no (yes)	51 (39)	68 (37)
Presence of a knee extensor lag: no (yes)	61 (29)	75 (30)

Assumptions of linearity were not violated, as assessed by partial regression plots and a plot of studentized residuals against the predicted values. There was independence of residuals, as assessed by a Durbin-Watson statistic of 2.266 for the group with diplegia and 2.111 for the group with hemiplegia. There was homoscedasticity, as assessed by visual inspection of a plot of studentized residuals versus unstandardized predicted values. There was no evidence of multicollinearity, as inspection of the correlation coefficients revealed that none of the independent variables had correlations larger than .7 and no tolerance values were greater than .1. The assumption of normality was met, as assessed by a histogram with a superimposed normal curve as well as a P-P Plot.

The final dataset used in the analysis included 90 individuals with diplegic CP (GMFCS level I, *n* = 35; GMFCS level II, *n* = 55) and 105 individuals with hemiplegic CP (GMFCS level I, *n* = 59; GMFCS level II, *n* = 46). A total of 118 individuals did not have a history of prior surgery (*n* = 48 with diplegia; *n* = 70 with hemiplegia). Further inspection of the data revealed that a total of 140 individuals did not exhibit the presence of hamstring spasticity, as defined by a score of zero on the Modified Ashworth Scale (*n* = 64 with diplegia; *n* = 76 with hemiplegia).

Similarly, a total of 119 individuals did not exhibit a deficit in knee extensor strength, as defined by a score of five on the Kendall scale (*n* = 51 with diplegia; *n* = 68 with hemiplegia). The ordinal variables of hamstring spasticity and knee extensor strength were converted to categorical variables (no presence/presence of hamstring spasticity; no deficit/deficit in knee extensor strength).

For participants with diplegic CP, the mean magnitude and timing of knee extension during terminal swing phase was 24.29° (SD = 9.7) and 99.63% (SD = .8) of the gait cycle, respectively. The magnitude of knee extension during terminal swing phase was higher (*p* = .021), as observed by a smaller value in degrees, in the group with hemiplegic CP, with a mean of 20.95° (SD = 10.3). The timing of peak knee extension during terminal swing phase occurred at a mean of 99.65% (SD = .8) of the gait cycle in the group with hemiplegia (Tables 2 and 3).

Table 2: Absolute and Correlation Data in Group with Diplegia. Pearson's or Spearman's correlation between main study variables and magnitude of knee extension in terminal swing phase.

	Mean (SD)	r/r_s	*p*	95% CI	
Variable				Lower	Upper
Magnitude of knee extension (°)	24.29 (9.7)	-	-	-	-
walk-DMC	74.42 (17.2)	-.39	<.001	-.554	-.201
Single limb support time (%)	37.07 (3.4)	.01	.892	-.193	.221
Knee extension ROM (°)	1.07 (5.9)	-.34	<.001	-.513	-.146
Ankle dorsiflexion ROM (°)	3.64 (8.0)	-.37	<.001	-.538	-.179
Normalized semitendinosus length	.99 (.0)	.10	.363	-.112	.298
Presence of hamstring spasticity	-	.16	.131	-.054	.361
Deficit of knee extensor strength	-	.18	.088	-.304	.379
Presence of a knee extensor lag	-	.31	.003	.103	.490
GMFCS level	-	.32	.002	.112	.497
History of prior surgery	-	-.10	.346	-.307	.115

Table 3: Absolute and Correlation Data in Group with Hemiplegia. Pearson's or Spearman's correlation between main study variables and magnitude of knee extension in terminal swing phase.

	Mean (SD)	r/r_s	*p*	95% CI	
Variable				Lower	Upper
Magnitude of knee extension (°)	20.95 (10.3)	-	-	-	-
walk-DMC	69.05 (13.3)	-.30	.001	-.472	-.123
Single limb support time (%)	40.69 (2.4)	.33	<.001	.149	.491
Knee extension ROM (°)	1.42 (4.8)	-.22	.022	-.397	-.032
Ankle dorsiflexion ROM (°)	-1.90 (11.3)	-.39	<.001	-.538	-.210
Normalized semitendinosus length	.99 (.0)	.04	.700	-.155	.228
Presence of hamstring spasticity	-	-.03	.738	-.229	.165
Deficit of knee extensor strength	-	.16	.109	-.041	.344
Presence of a knee extensor lag	-	.06	.517	-.135	.258
GMFCS level	-	.11	.286	-.094	.296
History of prior surgery	-	.03	.792	-.172	.222

Selective voluntary motor control, as measured by the walk-DMC, demonstrated a significant negative correlation with the magnitude of knee extension during terminal swing phase in both the group with diplegia ($r = -.39$, $p < .001$) and the group with hemiplegia ($r = -.31$, $p = .001$), such that improved SVMC was associated with increased knee extension at terminal swing phase. The mean walk-DMC score was higher ($p = .015$) in the group with diplegia (74.42, with a range of 42.80-111.90) as compared to the mean walk-DMC for the group with hemiplegia (69.05 with a range of 38.5-109.1).

Stance phase stability, as measured by single limb support time of the contralateral limb, was not significantly correlated with the magnitude of knee extension during terminal swing phase in the group with diplegia ($r = .01$, $p = .892$), while a significant positive correlation was observed in the group with hemiplegia ($r = .33$, $p < .001$). The mean single limb support time of the stance limb was lower ($p < .001$) in the group with diplegia (37.06% of the gait cycle), as compared to the group with hemiplegia (40.69% of the gait cycle).

Knee extension and ankle dorsiflexion joint ROM were significantly correlated with knee extension during terminal swing phase in both the group with diplegia ($r = -.34, p < .001$; $r = .37, p < .001$) and the group with hemiplegia ($r = -.22, p = .022$; $r = -.39, p < .001$), such that increased knee extension and ankle dorsiflexion ROM were associated with increased knee extension at terminal swing phase. A significant correlation was not observed between hamstring muscle-tendon length and the magnitude of knee extension during terminal swing phase for either group.

The stepwise multiple regression model (Table 4) populated with walk-DMC, knee extension ROM, ankle dorsiflexion ROM, and extensor lag in the group with diplegia (Model 1) was statistically significant, $R^2 = .324$, $F(4, 85) = 10.195$, $p < .001$, adjusted $R^2 = .292$. The addition of GMFCS level and history of prior surgery, as covariates, to the prediction of the magnitude of knee extension during terminal swing phase (Model 2) led to a statistically significant increase in R^2 of .111, $F(2, 83) = 8.163$, $p < .001$. Extensor lag, GMFCS level, and history of prior surgery were categorical variables, entered in this case as a zero or a one for no presence of an extensor lag versus presence of an extensor lag, GMFCS level I versus II, and no history of prior surgery versus history of prior surgery, respectively. Findings revealed that increased walk-DMC and greater knee extension and ankle dorsiflexion ROM were predictive of an increased magnitude of knee extension during terminal swing phase. The presence of an extensor lag was associated with decreased knee extension during terminal swing phase. Finally, increased GMFCS level and no history of prior surgery were associated with increased knee extension during terminal swing phase.

Table 4: Stepwise Multiple Regression Predicting Magnitude of Knee Extension in Terminal Swing Phase in Group with Diplegia.

Magnitude of Knee Extension During Terminal Swing Phase						
	Model 1			Model 2		
Variable	B	β	*p*	B	β	*p*
Constant	33.64		<.001	24.51		<.001
walk-DMC	-.121	-.216	.040	-.111	-.197	.052
Knee extension ROM	-.259	-.158	.110	-.396	-.241	.011
Ankle dorsiflexion ROM	-.398	-.330	<.001	-.374	-.310	<.001
Extensor lag	4.31	.209	.035	3.07	.149	.108
GMFCS level				6.35	.322	<.001
Prior surgery				-2.36	-.174	.051
R^2	.324			.435		
F	10.195			10.663		
ΔR^2	.036			.111		
ΔF	4.585			8.163		

The stepwise multiple regression model (Table 5) populated with walk-DMC, single limb support time of the contralateral limb, and ankle dorsiflexion ROM in the group with hemiplegia (Model 1) was statistically significant, $R^2 = .251$, $F(3, 101) = 11.308$, $p < .001$, adjusted $R^2 = .229$. The model including the covariates of GMFCS level and history of prior surgery (Model 2) was not statistically significant (R^2 of .006, $F(2, 99) = .418$, $p = .660$). Findings revealed that increased walk-DMC and greater ankle dorsiflexion ROM were predictive of increased magnitude of knee extension during terminal swing phase. Greater single limb support time of the stance limb was associated with decreased knee extension during terminal swing phase.

Table 5: Stepwise Multiple Regression Predicting Magnitude of Knee Extension in Terminal Swing Phase in Group with Hemiplegia.

Magnitude of Knee Extension During Terminal Swing Phase						
	Model 1			Model 2		
Variable	B	β	*p*	B	β	*p*
Constant	-3.90		.825	-8.84		.639
walk-DMC	-.168	-.217	.016	-.147	-.189	.058
Single limb support time	.883	.204	.027	.907	.210	.025
Ankle dorsiflexion ROM	-.276	-.303	<.001	-.278	-.305	.001
GMFCS level				1.69	.082	.367
Prior surgery				.208	.010	.910
R^2	.251			.258		
F	11.308			6.874		
ΔR^2	.085			.006		
ΔF	11.516			.418		

The stepwise multiple regression models used to predict the timing of peak knee extension during terminal swing phase were not statistically significant for either group with diplegia or with hemiplegia.

3.4 Discussion

Walking speed is directly related to step length and cadence. Given the influence of the position of the lower limb during swing phase on step length, the magnitude of knee extension during terminal swing phase can be considered a mediating factor for overall gait speed. In the current study, individuals with diplegic CP exhibited a mean of 24.29° of knee extension during terminal swing phase and individuals with hemiplegic CP exhibited a mean of 20.95° of knee extension. An increased magnitude of knee extension during terminal swing phase is represented by a smaller value in degrees. These findings are consistent with Daly (2021), whereby the mean value of knee extension during terminal swing phase was 27.6° in a group of individuals with diplegic CP (Daly, 2021). Further, the decreased magnitude of knee extension during terminal swing phase observed in the group with diplegia, as compared to the group with hemiplegia, in the current study, suggests that there may be a relationship with functional impairment.

The primary aim of this study was to examine factors associated with the magnitude of knee extension during terminal swing phase, including a task-specific measure of SVMC, such as the walk-DMC. In the current study, the VAF_1 for each participant was computed and scaled into a transformed *z*-score using normative values for VAF_1^{AVE} and VAF_1^{SD}, as reported in the literature. This was done in the absence of a sEMG database for TD individuals in our laboratory (MacWilliams et al., 2021). Using this approach, as well as the exact signal processing protocol of the raw sEMG data, we found that the mean and range for walk-DMC scores were similar to those reported by MacWilliams et al. (2021), whereby the mean walk-DMC values for GFMCS levels I, II, III participants were 92.8, 72.6, 67.2 respectively, and ranged from 46.0 to 121.3 (MacWilliams et al., 2021).

Several studies have explored the influence of impaired SVMC on terminal swing phase and initial contact. Selective voluntary motor control, as measured by the walk-DMC in the current study, demonstrated a significant negative correlation with the magnitude of knee extension during terminal swing phase in both the group with diplegia and the group with hemiplegia, such that improved SVMC was associated with increased knee extension at terminal swing phase. This finding is consistent with Zhou et al. (2019), whereby SVMC, as measured by the SCALE, was negatively correlated with ipsilateral knee flexion at initial contact ($r = -.42$, $p = .000$). The results from the current study further demonstrate that intact SVMC is essential during terminal swing phase, whereby hip flexion, knee extension, and ankle dorsiflexion occur concomitantly.

The results from our regression analysis are consistent with prior research, which suggest that decreased knee extension in terminal swing phase is multifactorial. In the group with diplegia, single limb support time of the stance limb, hamstring muscle spasticity, knee extensor strength, and hamstring muscle-tendon length all dropped out of the final model. Of the independent variables remaining in the model, SVMC, as measured by the walk-DMC, and ROM of the knee and ankle joints, were significant predictors of the magnitude of knee extension during terminal swing phase. While the presence or absence of an extensor lag of the knee joint met the criteria for inclusion in the stepwise regression model, it was not found to be a significant predictor in the final model. The findings partially support the authors' proposed hypothesis, such that SVMC was found to be a significant predictor of the magnitude of knee extension during terminal swing phase, while stance phase stability, as measured by single limb support time of the stance limb, was not a significant predictor in the group with diplegia.

In the group with hemiplegia, knee extension ROM, hamstring spasticity, measures of knee extensor strength, and hamstring muscle-tendon length all dropped out of the final model. All of the independent variables entered in the model, including walk-DMC, single limb support time of the stance limb, and ankle joint ROM, were significant predictors of the magnitude of knee extension during terminal swing phase. The findings partially support the authors' proposed hypothesis, such that SVMC was found to be a significant predictor of the magnitude of knee extension during terminal swing phase. Unlike the group with diplegia, single limb support time was found to be a significant predictor in the group with hemiplegia. Moreover, contrary to the proposed hypothesis, increased single limb support time was associated with decreased magnitude of knee extension during terminal swing phase. Single limb support time as a percentage of the gait cycle is defined by ipsilateral heel strike to contralateral heel strike.

To this end, single limb support time is influenced by advancement of the contralateral limb during swing phase, such that impairments of the swing limb (e.g. presence of a knee flexion contracture, impaired SVMC) alter initial contact, thereby resulting in a prolonged single limb support time on the opposite side. In the present study, the hemiplegic side was used for the variables associated with the swing limb. A leg length discrepancy, with a shorter limb observed on the involved side in individuals with hemiplegic CP, may have contributed to a delay in initial contact of the swing limb, further explaining the current results of increased single limb support time of the less impaired side (Riad et al., 2010). Taken together, these findings suggest that stance phase stability may not be representative of single limb support time, and that an alternative temporal distance measure, such as double-limb support time, could be a better surrogate.

The model including the covariates of GMFCS level and prior history of surgery improved the overall prediction, accounting for 44% of the explained variability in the magnitude of knee extension during terminal swing phase, in the group with diplegia. Individuals classified as GMFCS level II and those without a history of prior surgery demonstrated decreased knee extension during terminal swing phase. The addition of these covariates in the model for the group with hemiplegia did not result in a statistically significant increase in the overall prediction. The model, without the covariates, accounted for 25% of the explained variability in the magnitude of knee extension during terminal swing phase in the group with hemiplegia. These findings suggest that there are other factors that are associated with knee extension during terminal swing phase, such as lever arm disease or impaired postural control, that have not been explored in the current study.

While SVMC, as measured by the walk-DMC, remained a significant predictor of the magnitude of knee extension in both groups with successive models in the stepwise regression, ankle dorsiflexion ROM was the strongest predictor (e.g. highest beta coefficient) in the final model for both groups. These findings are consistent with Zhou et al. (2019), whereby more severe ankle equinus contractures were associated with increased knee flexion at initial contact ($r = .33$, $p = .000$) (Zhou et al., 2019). The influence of ankle dorsiflexion ROM on the position of the knee during terminal swing phase or initial contact is not surprising, given that the gastrocnemius is a two-joint muscle. Interestingly, Daly (2021) did not find a significant correlation between swing limb ankle kinematics and knee extension in terminal swing phase (Daly, 2021).

In the current study, hamstring spasticity and hamstring muscle-tendon length were not correlated with knee extension in terminal swing phase and were not entered into the stepwise regression model for either group with diplegia or hemiplegia. In comparison, Daly (2021) found that hamstring spasticity, which was present in 43.2% of the cohort, did not correlate with knee extension during terminal swing phase while reduced semitendinosus length at terminal swing was correlated ($r = .47$, $p < .0001$) (Daly, 2021). Prior research using musculoskeletal modelling to estimate the muscle-tendon length of the hamstrings demonstrated that 35% of participants walked with shortened hamstrings (Arnold et al., 2006). Further, Rha et al. (2016), found that SVMC, as measured by the SCALE, was a stronger correlate of knee flexion at initial contact as compared to a shortened semitendinosus muscle (Rha et al., 2016).

Findings from the current study have several important clinical implications for the treatment of gait pathology in children with CP. The results from the regression analysis demonstrate that decreased knee extension in terminal swing phase is multifactorial in both individuals with diplegic and hemiplegic CP and underscore the importance of discerning between primary, secondary, or tertiary causes of gait pathology. For example, treatment of decreased knee extension in terminal swing phase with a hamstring lengthening surgery, in the setting of impaired SVMC or an ankle equinus contracture, is not likely to lead to a restoration of the prerequisites of normal gait pertaining to adequate step length or prepositioning. Furthermore, the results emphasize the critical need for identifying patient-specific characteristics (e.g. GMFCS level, topographical distribution of CP) when considering interventions to address decreased knee extension during terminal swing phase. It is also important to recognize that these considerations may differ from those that are important when addressing limitations in knee extension during stance phase. Finally, results from the current study provide additional support for the utility of employing a task-specific measure of SVMC, such as the walk-DMC, when assessing the influence of impaired SVMC during gait.

There are several recognized limitations of this study. The study design was retrospective. The measurement methods used to assess muscle strength of the knee extensors and hamstring muscle spasticity are subjective. More objective approaches, such as handheld dynamometry or the Modified Tardieu Scale, could be considered. Another limitation of the study was the absence of a normative sEMG database, necessitating use of the reported mean and SD for VAF_1 in a TD group when calculating walk-DMC scores. Finally, a cross-validation procedure was not performed to assess the robustness of the models.

In conclusion, intact SVMC is essential during terminal swing phase, whereby hip flexion, knee extension, and ankle dorsiflexion occur concomitantly. Decreased knee extension in terminal swing phase in individuals with CP is multifactorial and is not simply the result of tight hamstrings or weak knee extensors. Furthermore, limitations in knee extension in terminal swing phase may be compensatory. As such, a patient-specific approach should be undertaken when considering certain interventions to address this gait impairment. Including task-specific measures of SVMC, such as the walk-DMC, is essential when using IGA in assessing gait pathology to inform clinical decision-making and to predict outcomes following treatment.

Conclusion

Selective voluntary motor control (SVMC) is one of many impairments that is related to gait pathology in individuals with cerebral palsy (CP). Quantifying motor control is challenging, however, there are several approaches available to assess SVMC in individuals with CP. The Selective Control Assessment of the Lower Extremity (SCALE), which was developed as an objective clinical assessment method of SVMC in children with CP, is easy to administer and does not involve the use of specialized equipment (Fowler et al., 2009). Yet, it has been suggested that the testing procedure involves non-functional movements, the assessment is subjective, and the ordinal scoring system may lack the sensitivity necessary to measure small changes in SVMC (Balzer et al., 2017a; Schwartz et al., 2016). The more recent use of muscle synergy analysis has been proposed as an objective method to measuring SVMC during the functional task of walking. The Walking Dynamic Motor Control Index (walk-DMC) was developed to quantify the complexity of neuromuscular control during walking (Steele et al., 2015). We found the walk-DMC to have a strong positive correlation with the SCALE ($r = .64$, $p \leq .0001$), demonstrating additional concurrent validity of the walk-DMC and offering further support for synergy analysis as a measure of SVMC in this population.

Prior to further evaluating the validity of the walk-DMC as a measure of SVMC in children with CP, the authors examined walk-DMC scores across GMFCS levels using the mean and standard deviation (SD) for the total variance accounted for by one synergy (VAF_1) as reported in the literature, in the absence of a database of surface electromyography (sEMG) data for typically developing (TD) individuals. When employing this novel approach, we found that walk-DMC scores were significantly different across GMFCS levels and that decreased SVMC was observed in those individuals with greater functional impairment, which is consistent with existing literature (Steele et al., 2015). This finding is promising for other laboratories without a sEMG database for TD individuals, who are interested in incorporating synergy analysis as part of their clinical gait analysis standard of care.

The ability to walk and keep up with peers is an important goal amongst children with CP and their caregivers. As such, factors associated with decreased walking speed are of interest amongst clinicians and researchers. Adequate step length and pre-positioning of the lower limb during swing phase, each prerequisites of normal gait, are directly related to gait speed. Decreased knee extension during the terminal swing phase of gait is one of a variety of factors that contributes to inadequate step length in children with CP (Arnold et al., 2007). Impaired SVMC, as measured by walk-DMC, was found to be a significant predictor of decreased knee extension during terminal swing phase. Furthermore, employing a task-specific measure of SVMC, such as the walk-DMC, is recommended when assessing the influence of impaired SVMC during gait.

Decreased knee extension in terminal swing phase in individuals with CP is multifactorial and is not simply the result of tight hamstrings or weak knee extensors, underscoring the complexity of gait pathology in this population. As such, a patient-specific approach should be undertaken when considering certain interventions to improve the walking ability of children with CP. Furthermore, including task-specific measures of SVMC, such as the walk-DMC, is essential when using IGA in assessing gait pathology to inform clinical decision-making and predict outcomes following treatment.

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