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The effect of lower extremity selective voluntary motor control on interjoint coordination during gait in children with spastic diplegic cerebral palsy

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ABSTRACT

Damage to motor tracts in the periventricular white matter is a primary etiology in spastic diplegic cerebral palsy (CP). These tracts are responsible for the production of selective voluntary motor control (SVMC). Lower extremity motor control has been suggested as being an important predictor of improvement following interventions. While there are multiple impairments in spastic CP, the inability to perform purposeful voluntary movement is a critical factor in determining functional ability that merits investigation. The purpose of this study was to examine the relationship between SVMC ability and hip and knee coordination during the swing phase of gait in participants with spastic CP. Gait analysis and SVMC assessments were conducted for 15 participants with CP. Relative phase analysis was used to calculate the minimum relative phase (MRP) angle during swing; a measurement of interjoint coordination between the hip and the knee. SVMC ability was measured using the Selective Control Assessment of the Lower Extremity (SCALE) tool. Significant correlations were found between SCALE scores and both MRP values ($p < 0.0001$) and duration of out-of-phase movement ($p < 0.005$) during swing. These findings supported our hypothesis that SVMC ability is related to a patient's ability to move in an uncoupled pattern during the swing phase of gait (i.e., extending the knee while flexing the hip). An understanding of influence of SVMC on swing phase gait mechanics may help establish appropriate goals for interventions, in particular hamstring lengthenings.

1. Introduction

Damage to motor tracts in the periventricular white matter is a primary etiology in spastic diplegic cerebral palsy (CP) [1]. These tracts, including the corticospinal tracts, are responsible for the production of selective voluntary motor control (SVMC). On clinical examination, patients with impaired or absent SVMC may exhibit reduced speed of movement, mirror movements or abnormal reciprocal muscle activation [2]. In addition, they are often unable to move the hip, knee and ankle joints independently of one another relying on closely coupled flexion and extension patterns to varying degrees [3]. Historically, pathological coupled joint flexion or coupled joint extension movements observed for patients with upper motor neuron lesions have been described as flexor or extensor synergy patterns [4]. These patterns normally occur during kicking in the young infant but decoupling patterns emerge as more skilled and complex movements are developed [5,6]. Children with CP who have reduced ability to develop the selective motor control necessary for skilled movements may develop movement strategies that retain primitive coupled patterns to various degrees. Preliminary evidence suggests that SVMC ability may be an important factor affecting functional movement tasks [7,8] and may be predictive of improvement following interventions [9]. Despite these clinical findings, the role of SVMC has not been explored as a factor that can affect biomechanics during walking in children with CP.

Inadequate peak knee extension during the swing phase of gait is an identified problem in patients with CP [10–12]. This finding has been related to spastic hamstrings [10,12,13], static hamstring contractures [11,13] and premature firing of the hamstrings [14]. Hamstring lengthenings are frequently performed to improve swing phase extension by increasing the muscle length and, thereby, decreasing the effect of spasticity. Although terminal knee extension may improve following lengthening, improvements are not consistent across participants, and peak knee extension does not typically approach normative values. Thometz et al. [15] analyzed gait in patients undergoing hamstring lengthenings and found that average knee position at initial contact improved from 49° to 30° of flexion, in contrast to a position between 0° and 10° flexion in individuals without disability [16]. Others have reported similar

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findings in knee position at initial contact following hamstring lengthenings [13,17,18]. Baumann et al. [13] reported that passive knee range of motion assessed using a goniometer improved to a much greater extent than that observed during swing, indicating that not all of the increased muscle length was utilized during walking.

Knee extension appears to improve to a greater extent during stance, as opposed to swing, following hamstring lengthenings [13,18]. Variation in SVMC impairment may explain these findings. During stance, the hip and the knee normally extend (appropriate coupling), while during swing, the hip normally flexes while the knee extends (uncoupled movement). During terminal swing, co-activity of the hamstrings and quadriceps, concurrent with hip flexor recruitment, normally occurs. Thometz et al. [15] identified a subset of patients with hamstring activity but diminished or absent quadriceps activity during terminal swing. This abnormal recruitment pattern suggests inappropriate flexor coupling. Patients with poor SVMC may be unable to dissociate hip and knee recruitment resulting in reduced knee extension during terminal swing regardless of hamstring length.

While there are multiple impairments in spastic CP, the inability to perform purposeful voluntary movement is a critical factor in determining functional ability that merits investigation. We have developed a clinical tool entitled "Selective Control Assessment of the Lower Extremity" (SCALE), an objective tool to quantify lower extremity SVMC in patients with spastic CP. The content validity and preliminary inter-rater reliability have been examined, and publications are in progress [19]. The purpose of this study was to examine the relationship between SCALE scores and interjoint coordination of the hip and knee during the swing phase of gait in participants with spastic CP. We hypothesized that SVMC ability measured using this tool is related to a patient's ability to move in an uncoupled pattern during swing.

2. Methods

2.1. Study population

Fifteen participants with CP were recruited for this study. Informed consent and assent, approved by the Institutional Review Board Human Subject's Protection Committee of our institution, were obtained for all participants.

Inclusion criteria for all participants were (1) age between 6 and 21 years, (2) ability to follow simple verbal directions, (3) diagnosis of spastic diplegic CP and (4) ability to walk independently for short distances, with or without assistive devices (Gross Motor Function Classification System (GMFCS) Levels I–IV) [20].

Exclusion criteria for all participants were (1) orthopedic or neurological surgery within the preceding 12 months, (2) botulinum toxin injections or serial casting within the preceding 3 months and (3) "stiff-knee gait" pattern. A participant was classified as having a "stiff-knee" gait pattern if he/she met the criteria described by Goldberg et al. [21].

2.2. Selective voluntary motor control assessment

SVMC was assessed using the SCALE tool [19]. Participants were tested by one of the three experienced physical therapists using a standardized protocol. The hip, knee, ankle, subtalar and toe joints were evaluated bilaterally. SCALE was administered by asking the participant to perform specific isolated movement patterns at each joint. Hip flexion and extension with the knee extended was tested in side lying. The remaining tests were performed in sitting: knee extension and flexion; ankle dorsiflexion and plantar flexion with the knee extended; subtalar inversion and eversion; and toe flexion and extension. Participants were asked to move in a reciprocating pattern to a verbal cadence (e.g., "flex, extend, flex"). SVMC was graded at each joint as "Normal" (2 points), "Impaired" (1 point) or "Unable" (0 points). A grade of "Normal" was given when the desired movement sequence was completed within a 3-s verbal count without movement of untested joints. A grade of "Impaired" was given when the participant was able to isolate motion during part of the task, but demonstrated any of the following features: movement in only one direction, movement less than 50% of available passive range of motion, movement at untested lower extremity joints (including mirror movements) or movement duration greater than the 3-s verbal cadence. A grade of "Unable" was given when the participant did not initiate the requested movement sequence or performed a tightly coupled movement pattern. An overall SCALE score for each limb was calculated by summing the points assigned to each joint for a maximum of 10 points per limb.

2.3. Gait analysis

Gait analysis was performed in the Kameron Gait and Motion Analysis Laboratory. An Eagle eight-camera system (Motion Analysis Corporation, Santa Rosa, CA) sampling at 60 Hz was used to collect motion analysis data. Fifteen reflective markers were placed on the participant using a modified Helen Hayes marker set [22]. Participants wore shorts and walked barefoot at a self-selected pace. Each walked back and forth on a 25-foot walkway until at least 10 gait cycles had been recorded for each limb. Handheld assist was provided for balance if required during walking. Data were collected in EVaRT 5.0 (Motion Analysis Corp., Santa Rosa, CA). Marker position data were smoothed using a Butterworth filter at 6 Hz [23]. Kinematics were calculated in Orthotrak 6.51 (Motion Analysis Corp.) using methods provided by Kadaba et al. [24]. All data were normalized to 100% of the gait cycle for comparison across participants. The gait cycle was defined from foot strike to foot strike. Each trial was divided into gait cycles, which was then averaged for each participant. All trials were checked for consistency, and aberrant trials were disregarded.

2.4. Relative phase analysis

Hip–knee angle diagrams were plotted for each limb. The curves were qualitatively assessed using conventions described by Winstein and Garfinkel [25]. The specific point of interest on the angle–angle plots was the portion of the swing phase in which simultaneous hip flexion and knee extension normally occur. If a turning point synchronization with a positive trajectory slope was present (i.e., both joints reach their maxima and switch simultaneously), the limb was described as moving in an abnormal coupled pattern for this phase of gait. If there was a phase offset (i.e., rounded trajectory), the limb was described as moving in an uncoupled pattern.

Relative phase analysis [26] was used to quantify interjoint coordination of the hip and knee during the swing phase of gait. Relative phase angles were calculated throughout the gait cycle using the following equation:

$$\Theta_{\mathrm{RP}} = \alpha_{\mathrm{Knee}} - \alpha_{\mathrm{Hip}} \quad (1)$$

where Θ_{RP} = relative phase angle, α_{Knee} = knee phase angle and α_{Hip} = hip phase angle. Eq. (1) yields relative phase values between $\pm 180^\circ$. A relative phase angle close to zero indicates that the two joints are moving in-phase; a relative phase angle approaching $\pm 180^\circ$ indicates that the joints are moving out-of-phase. A positive value indicates that the hip is leading the knee in the phase space. A negative value means the knee is leading the hip. The minimum relative phase (MRP) angle during swing was correlated with the SVMC clinical score (SCALE) for each limb using Spearman's rank correlation (r_S).

The steps involved in calculating the relative phase angles are shown in Fig. 1. Time series kinematic data were first calculated for the hip and the knee. Velocity-angle phase portraits were plotted, and phase angles were computed, as given by the following equation:

$$\alpha = \tan^{-1}\left(\frac{\dot{\theta}}{\theta}\right) \quad (2)$$

where $\dot{\theta}$ = angular velocity, and θ = angular displacement. Eq. (2) yields phase angle values between $\pm 90^\circ$. These phase angles were used to compute the relative phase using Eq. (1).

Previously, intersegmental coordination has been assessed using segment angles with respect to the fixed horizontal [26–28]. In the present study, our focus was interjoint coordination; therefore, we used joint angles in the anatomical reference frame consistent with Burgess-Limerick et al. [29]. Using the anatomical reference frame was necessary for two reasons: (1) this reference frame prevents motion of one joint from affecting the phase angle of the other joint. For example, moving the thigh segment relative to the fixed horizontal results in concomitant changes in the shank phase angle in the absence of knee joint motion. (2) Hip flexion with knee extension, an uncoupled motion, is mathematically "out-of-phase". Using a fixed horizontal reference frame, this movement pattern would have increased both the thigh and the shank angle, defined mathematically as "in-phase" motion.

In addition to the maximum amount of out-of-phase movement (MRP), the duration of out-of-phase movement during swing was of interest. To quantify this measure, the duration (% gait cycle) of simultaneous hip flexion and knee extension velocity during swing was computed. Duration was correlated with SCALE score for each limb using Spearman's rank correlation (r_S).

3. Results

Participants with low SCALE scores (e.g., Fig. 2A and B) demonstrated features consistent with turning point synchronization and a positive trajectory slope during swing, indicating tightly coupled movement. Hip and knee flexion occurred simultaneously during early swing. During mid-swing, both joints reached peak flexion and reversed direction at approximately the same time so that the hip and knee extended simultaneously during terminal

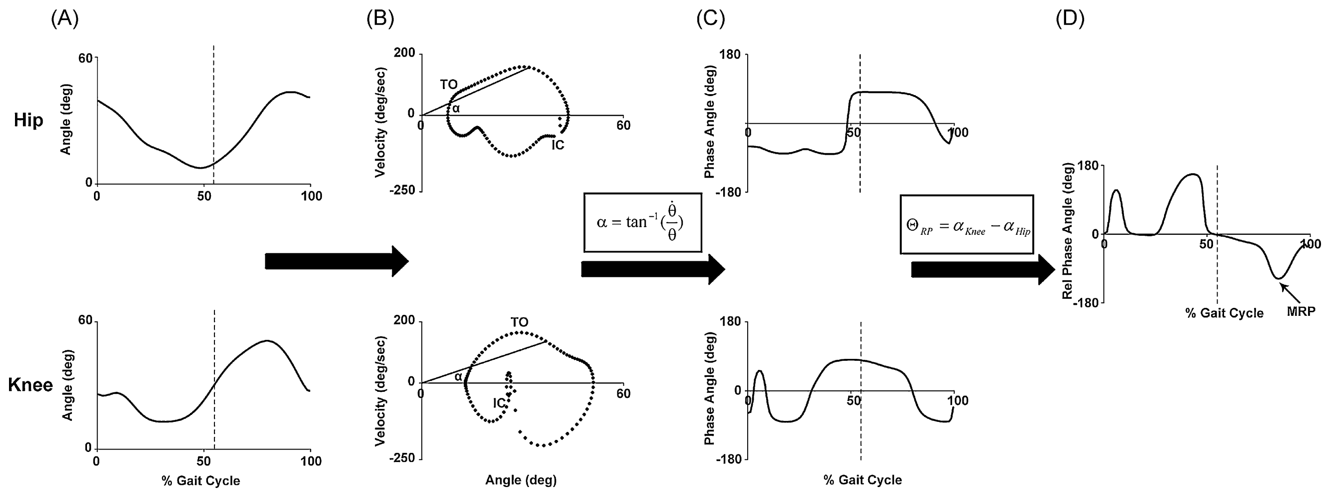

Fig. 1. Exemplar data for a child with CP illustrating the steps used to calculate relative phase angles between the hip and the knee. (A) Time series kinematic data, (B) velocity-angle phase portraits, (C) phase angles (α) and (D) relative phase angles throughout the gait cycle. The minimum relative phase (MRP) angle during the swing phase of gait was identified. Toe-off is indicated by the vertical dotted line for the time series, phase angle and relative phase plots. Positive values indicate flexion and negative indicate extension for angle and velocity plots. For the phase portraits, IC = initial contact and TO = toe off.

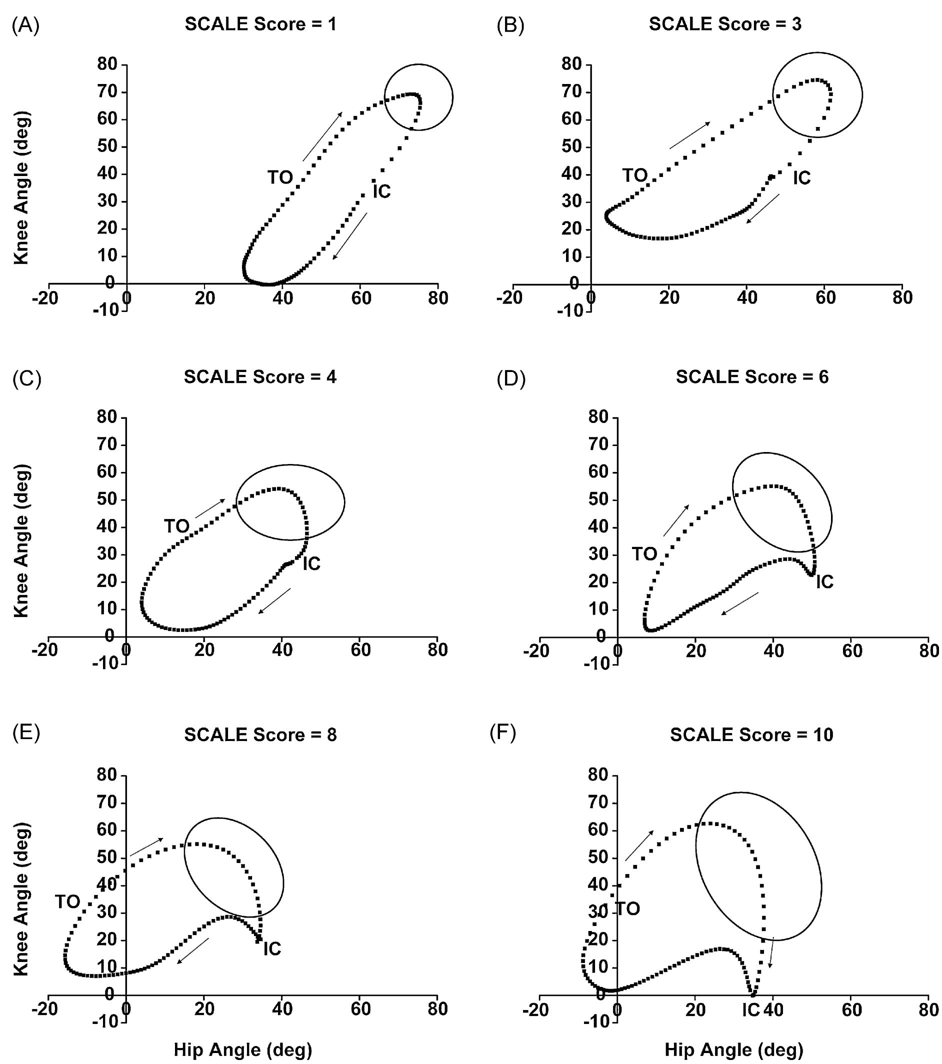

Fig. 2. Exemplar hip–knee angle diagrams for participants with a range of SCALE scores. (A–E) for participants with CP. A diagram for a child without disability (F) is provided, for comparison purposes. Initial contact (IC) and toe-off (TO) are indicated on each plot. Circled regions of the graphs indicate the portion of the gait cycle where hip flexion with simultaneous knee extension occurred. These regions encompassed a greater portion of the gait cycle for participants with higher SCALE values. Positive values indicate flexion and negative indicate extension.

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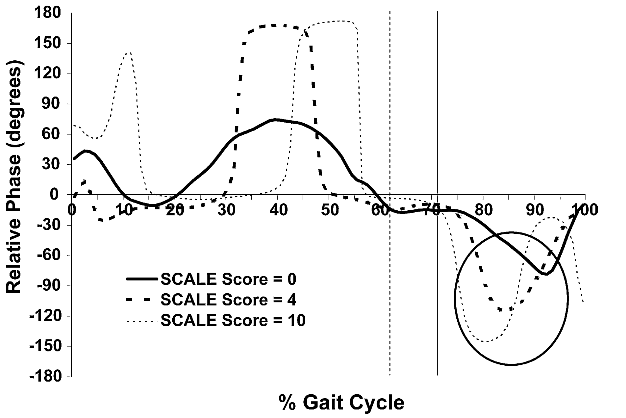

Fig. 3. Exemplar relative phase plots for participants' limbs with SCALE score = 0 and 4 and a subject without disability (SCALE score = 10). The circle indicates the region where minimum relative phase (MRP) angle was selected. Toe-off is indicated by the solid vertical line for the participant with SCALE score = 0 and by the dotted vertical line for the participants with SCALE scores = 4 and 10.

swing. Participants with SCALE scores of 4, 6 and 8 demonstrated a phase offset during swing (Fig. 2C–E), indicating an appropriate uncoupled movement. The relationship between hip and knee motion became closer to normal (Fig. 2F) with increasing SCALE scores. In addition, the range of motion and joint velocity increased with increasing SCALE scores as indicated by the greater distance between data points.

Exemplar continuous relative phase plots demonstrate the differences found for MRP values for limbs with different SCALE scores (Fig. 3). The limb with the greatest impairment in SVMC (SCALE score = 0) was slowest to reach a low MRP (−79°). In contrast, the curve of the limb with moderate SVMC impairment (SCALE score = 4) achieved an MRP of greater magnitude (−115°) earlier in swing. Overall, the curve of this limb better approximated that of the participant without disability (SCALE score = 10, MRP = −145°).

A significant relationship between MRP, which occurred at 87% gait cycle (S.D. = 3.5, range = 79–92), and SCALE scores was found (Fig. 4A–C). There was a strong relationship when the scores for both limbs were combined ($r_S = -0.83$, $p < 0.0001$) (Fig. 4A). As

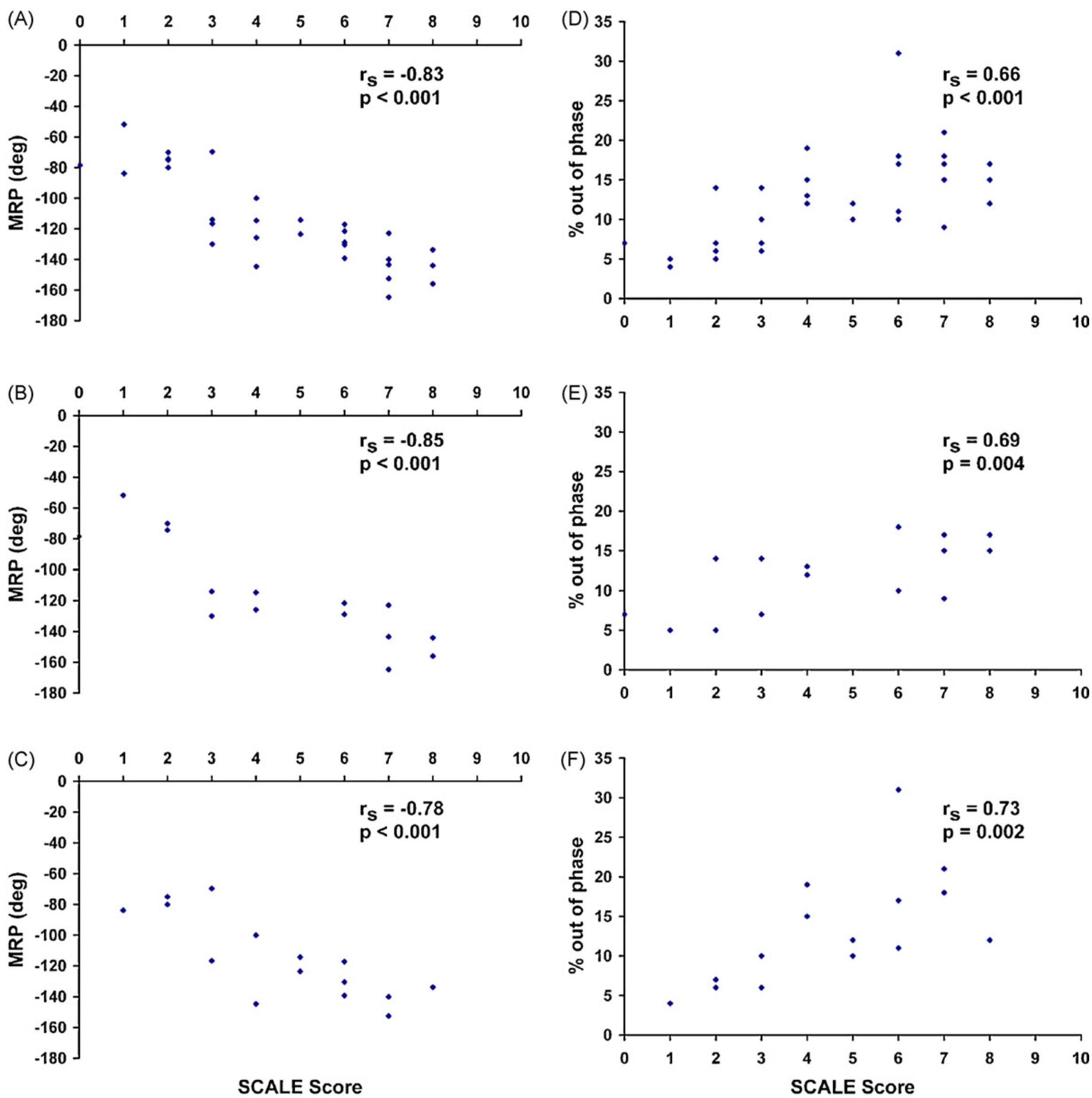

Fig. 4. Minimum relative phase (MRP) angle vs. SCALE scores for (A) all limbs, (B) left limbs and (C) right limbs. The portion of gait cycle where hip flexion with simultaneous knee extension occurred (% out of phase) versus SCALE scores for (D) all limbs, (E) left limbs and (F) right limbs.

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lower limbs are not completely independent of one another, separate relationships also were examined. Results for both left and right limbs demonstrated a significant correlation between MRP during swing and SCALE scores ($r_S = -0.85$ for left, $r_S = -0.78$ for right, $p < 0.0001$) (Fig. 4B and C).

Exemplar hip and knee velocity plots demonstrate variations in joint velocities across the spectrum of SCALE scores (Fig. 5). Participants with reduced SVMC ability (Fig. 5A and B) exhibited appropriate uncoupled movements for shorter durations during swing, while participants with greater SVMC ability exhibited appropriate uncoupled motion (Fig. 5C–E) for longer durations. Participants with SCALE scores of 6 and 8 had velocity curves that approximated that of the subject without disability (Fig. 5D–F). A significant relationship between the duration of appropriate "out-of-phase" movement during swing and SCALE scores was found ($r_S = 0.66$ for all limbs, $r_S = 0.69$ for left, $r_S = 0.73$ for right, $p < 0.005$) (Fig. 4D–F).

4. Discussion

These findings supported our hypothesis that SVMC ability measured using the SCALE tool is related to a patient's ability to perform uncoupled hip and knee movement during the swing phase of gait. This relationship was evident qualitatively using hip–knee angle diagrams and quantitatively by the significant correlation between SCALE scores and MRP during swing. In addition, subjects with higher SCALE scores could maintain uncoupled activity for longer durations during swing. These data suggest that clinical examination of SVMC ability is predictive of coordinated movement during the swing phase of gait.

Large standard deviations for swing phase knee extension following hamstring lengthenings in patients with CP have been reported [13,17,18], suggesting a wide range of results. However, SVMC was not evaluated. Variations in SVMC ability may have influenced these results. Patients with poor SVMC ability may be constrained by their neurological capability and unable to dissociate hip and knee movement during swing regardless of hamstring length. Patients with good SVMC ability, initially constrained by biomechanical factors, may be able to utilize their increased range of motion following hamstring lengthenings. An understanding of influence of SVMC on swing phase mechanics during gait may help establish more realistic goals for interventions, in particular hamstring lengthenings.

Several investigators propose normalizing velocity-angle curves before calculating phase angles to prevent one angle from dominating the continuous relative phase plot [29–31]. In

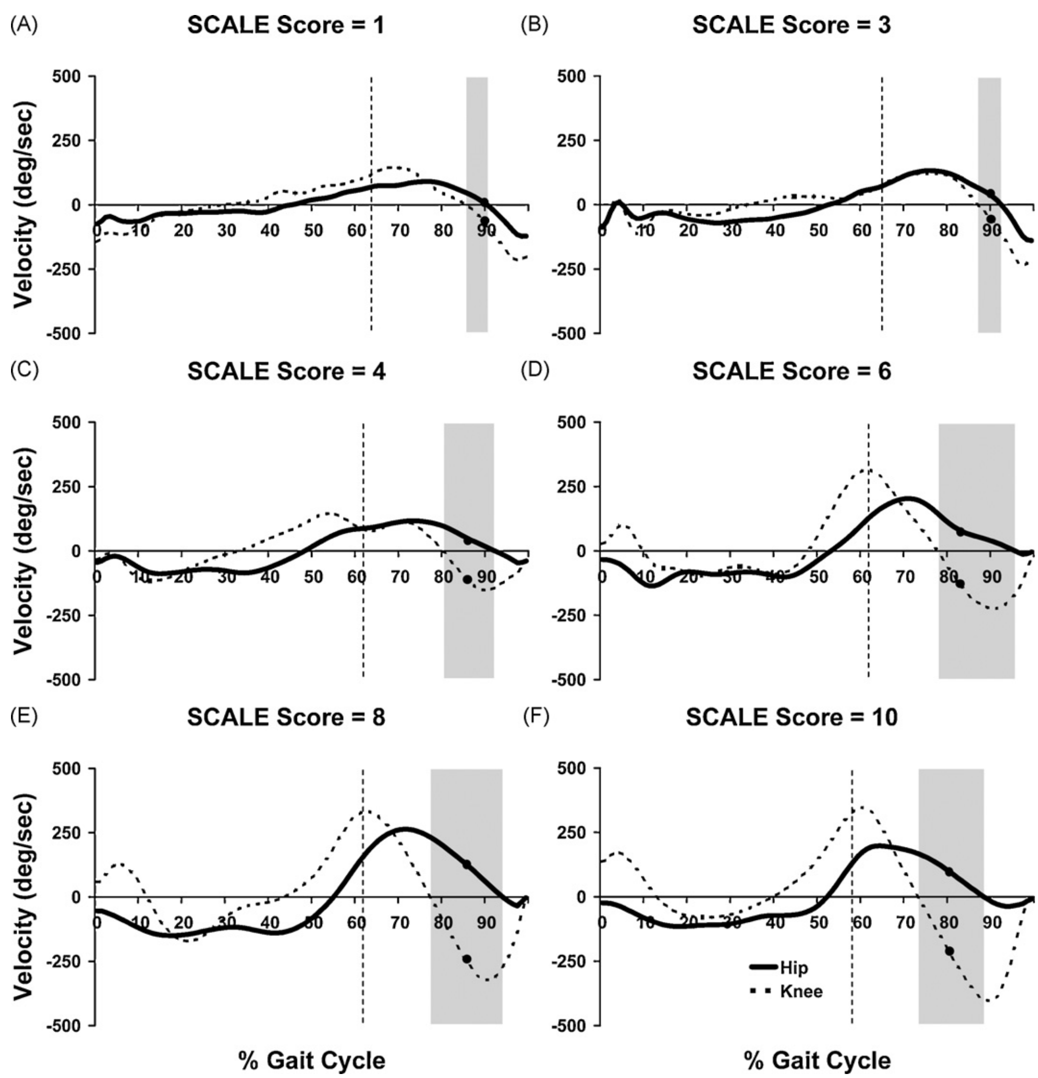

Fig. 5. Exemplar hip and knee velocity plots for participants with a range of SCALE scores. (A–E) for participants with CP. Data for a child without disability (F) is provided, for comparison purposes. Vertical dotted line indicates toe-off. Shaded regions indicate simultaneous hip flexion and knee extension velocity. Large dots on the velocity curves represent the point in the gait cycle where MRP occurred. Positive values indicate flexor and negative indicate extensor velocity.

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contrast, Kurz and Stergiou [32] argued that the arc tangent function accounts for differences in angle amplitudes, and normalizing would cause some of the dynamic qualities to be lost. In the present study, normalizing the data would have masked differences in range of motion and velocity between joints and participants. As these are important determinants of selective motor control ability, we did not normalize our data.

We did not include patients with "stiff-knee gait", characterized by inadequate peak knee flexion and knee range of motion during the swing phase of gait [21]. MRP is a measure interjoint coordination during simultaneous hip flexion and knee extension. These patients walk with sufficient hip joint excursion but minimal knee joint excursion resulting in a measure of joint coordination (MRP) that is misleading.

Our data suggest that the SVMC ability of the stance phase limb may influence interjoint coordination of the swing limb. Five of the fifteen participants had a difference of at least two SCALE score points between left and right limbs. In all five cases, the MRP of the limb with the lower score was greater in magnitude and similar to the MRP of the opposite limb with the higher SCALE score. For example, one participant with SCALE scores of 4 and 7 on the right and left limbs, respectively, had MRP of -145° on the right and -143° on the left. Arnold et al. [33] demonstrated the contribution of stance limb musculature to swing limb terminal knee extension using induced acceleration analysis. Siegel et al. [34] used similar methodology to demonstrate the positive effect of intralimb coordination on the control of energy flow throughout the lower extremities. The stance limb in these particular participants may be compensating for the lack of swing limb SVMC ability by generating and transferring energy.

The mechanisms associated with response to therapeutic intervention are complex and dependent on factors that are associated with the individual and the treatment. A wide range of responses to treatment for inadequate swing phase knee extension has been reported for this patient population. The SCALE tool is a fairly simple clinical measure that provides insight into a patient's neurological control over his/her hip and knee coordination during swing. The information gleaned from this study can be used to develop protocols for future studies examining functional outcomes following interventions such as hamstring lengthenings across the spectrum of SVMC impairment. SVMC ability may guide the selection of other rehabilitation interventions, particularly in the area of motor learning.

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Conflict of interest

None.

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