Use of Relative Phase as a Measure of Motor Control at the Ankle in Persons With Cerebral Palsy: A Preliminary Study

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This investigation developed a measure of motor control at the ankle for persons with CP using relative phase. Twenty-nine subjects, 14 with spastic diplegia cerebral palsy (CP group) and 15 without disability (WD group) were tested once. Video data were collected as a seated subject performed four full range of ankle plantar and dorsiflexion movement tasks (right ankle, left ankle, ankles in-phase with each other, and ankles antiphase to each other) at four different frequencies (self-paced, 0.5, 0.75, 1.0 Hz). The relative phase measure was able to discern the differences between the two groups of children. The CP group had poorer motor control than the WD group, based upon the measure. Both groups had more difficulty performing the antiphase than the in-phase movements. The investigation adds to the body of knowledge in that the concept of relative phase was used as a measure of motor control at the ankle in persons with CP. Results indicated that the measure was adequately sensitive to quantify differences between a group with CP and a group without disability. Clinically the measure could eventually be used as both an assessment and outcome tool.

Keywords: cerebral palsy, motor control, ankle, relative phase

Cerebral palsy (CP) is a nonprogressive disorder characterized by impairment of motor function secondary to injury of the immature brain (Ingram, 1984). Problems within the impairment domain for CP include such things as spasticity, strength, motor control, and balance. Clinicians treat many of these impairments in an attempt to improve the function of individuals with CP. For example, tendon transfer surgeries are performed on persons with CP to improve motor control and, thereby, improve function.

Even though many treatments exist to alter impairments, few measures exist to quantify their effects. This lack of quantification limits the understanding and interpretation of the treatments. Objective measures exist to quantify spasticity, strength, and balance (Cherng et al., 1999; Engsberg et al., 1996, 1998; Nashner et al., 1983). Gage (2004) lists motor (muscle) control as one of five peripheral manifestations occurring with growth and development in children with CP: (1) lack of selective muscle control, (2) dependence on primitive reflex patterns for ambulation, (3) abnormal muscle tone, (4) relative imbalance between muscle agonists and antagonists across joints, and (5) deficient equilibrium reactions. Objective measures have been used to quantify motor control (i.e., the regulation of movement, Newton, 1990) of the upper extremity and knee in patients with CP (Engsberg et al., 2001; Harrison, 1975). However, no objective measure currently exists that quantifies motor control at the ankle in persons with CP. Our attempts at adapting our knee motor control measure to the ankle have been unsuccessful due to ankle muscle weakness (Engsberg et al., 2001). For example, with the ankle being passively rotated through its range of motion, a nominal force of about 20% of maximum was difficult to control.

The importance of such a measure at the ankle comes from our previous research attempting to predict changes in gait speed and the gross motor function measure (GMFM) in children with CP undergoing a selective dorsal rhizotomy (Engsberg et al., 2007). While a significant amount of variance could be explained from the predictor variables, the 95% confidence intervals were too broad to make clinically relevant predictions. We hypothesized that additional
measures were needed to increase the amount of explained variance and decrease the 95% confidence intervals. We had already developed measures for spasticity and strength and had used them in our predictions (e.g., Engsberg et al., 1996, 1998), but we had not used any measures of motor control in our predictions because none existed at that time. Subsequently, we developed a measure of motor control at the knee (Engsberg et al., 2001) and a measure of lower extremity joint (ankle, knee, hip) synergy (Olree et al., 2000), but we lacked a measure of motor control at the ankle. We believed a measure of motor control at the ankle was critical based on our preliminary research investigating the effects of ankle strengthening on gait speed and the GMFM in children with cerebral palsy (Engsberg et al., 2006). Our preliminary results supported the notion that gait speed and GMFM could be improved with ankle strengthening.

Relative phase (a quantification of the relative timing between a pair of oscillators at the same frequency) has been used extensively in populations without disability to measure motor control and coordination at various joints, particularly in the upper extremities (Collins et al., 1996, 1998; Haken et al., 1985). These techniques when applied to the upper extremity have the advantage of not having a substantial muscular strength requirement for completion. In most instances, only gravity needs to be overcome. Relative phase has been used in the lower extremities in persons with and without disability (Barela et al., 2000; Burgess-Limerick et al., 1993; Geuze, 2001; Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005; Van Emmerik et al., 1999; Volman and Geuze, 1998). Relative phase techniques have not been used to assess changes in movement coordination at the ankle in CP. The purpose of this investigation was to develop a measure of motor control at the ankle for persons with CP using relative phase. A first step in this development was to quantify differences between persons with CP and those without disability (WD). Given the preliminary nature of this work, specific hypotheses for each variable seem premature.

Methods

Subjects

A convenience sample of 29 subjects from the St. Louis area were recruited for this investigation by word of mouth. Fourteen of the subjects (16 ± 10 years, 5 males, 9 females) who had been diagnosed with spastic diplegia cerebral palsy (CP group). Fifteen of the subjects (15 ± 9 years, 7 males, 8 females) were without any known disability (WD group). The CP group was able to ambulate either with or without orthotics, walkers, canes, or crutches (Gross Motor Function Classification System (GMFCS) level I = 5, GMFCS level II = 8, GMFCS level III = 1). The CP group had adequate cognitive skills to participate in the study, no surgical procedures or other interventions (e.g., Baclofen, Botox) within the preceding year, and no previous selective dorsal rhizotomy. The CP group had a history (e.g., prematurity, low birth weight), clinical, or MRI findings consistent with the diagnosis of spastic diplegia. Subjects for the CP group were excluded if they had motor deficits secondary to neurological injury/illness beginning after the first month of life, moderate-to-severe dystonia, athetosis, or ataxia. All subjects and/or parent signed a human consent form approved by the Washington University Human Studies Committee. It should be noted that while all subjects in the CP group met reasonably strict criteria for inclusion in the study, the age range was large, including both children and adults. The large age range was intentional to obtain information across a broad spectrum. The WD group was age matched to have a similar spectrum.

Data Collection

Before data collection, each subject had reflective surface markers placed at the following locations: (1) rostral aspect of the fifth metatarsal head, (2) posterior aspect of calcaneus, (3) lateral malleolus, (4) lateral condyle of femur, (5) greater trochanter of femur, and (6) iliac crest. To collect the data, each person was seated on a table in an upright sitting position with feet not touching the ground (Figure 1). The leg was supported on a pad to allow the subject to see the foot. Video data were collected from a 6-camera HiRes Motion Analysis Corporation system (60 Hz) as the subject performed a series of ankle movements. Ten repetitions of full range of dorsiflexion–plantar flexion movement were used as a warm-up because it would mimic the measured movement patterns.

After completing the warm-up, subjects attempted four different movement tasks. For Task 1, subjects attempted to move the right ankle up and down (through their full dorsiflexion and plantar flexion range) as smoothly as possible. Pauses when changing direction were discouraged. Task 2 was identical to Task 1 except that it was performed with the left ankle. For Task 3, subjects attempted in-phase movements (synchronous movements of bilateral dorsiflexion and then bilateral plantar flexion). For Task 4, subjects attempted anti-phase movements (e.g., right dorsiflexion and left plantar flexion followed by right plantar flexion and left dorsiflexion).

Each movement task was performed at four different frequencies or paces for a period of 15 s. The first speed was self-paced. The second, third, and fourth paces were 0.5, 0.75, and 1.0 Hz, respectively. The last three paces used a metronome to help the subjects attain the appropriate pace. Subjects were instructed to move their ankle(s) in time to the metronome beeps. The beeps indicated when maximum dorsiflexion and plantar flexion should be achieved. Hence, a movement test consisted of 16 trials: 4 movement tasks (right ankle,
Data Analysis

Video data from the ankle ROM tests were tracked to produce three-dimensional locations for the surface markers and were reduced to sagittal plane ankle angles as functions of time. For this preliminary investigation, movements outside the sagittal plane were ignored. Numerical derivatives were calculated from the angle data.

The processing of the angle data to relative phase was then performed (Collins et al., 1996). The phase angle measures progression within a cycle. It is calculated as the arctangent of angular velocity divided by angle (with angular velocity normalized by dividing by the movement frequency to permit comparison across frequencies). The measure of relative phase (Figure 2, bottom; scaled from \(-\pi/2\) to \(3\pi/2\)) then provides a difference between the ankle phase angles, where the right phase angle is being subtracted from the left phase angle. The standard deviation within a trial of the relative phase measure \(\phi_{SD}\) (measured in degrees) was used to quantify motor control variability. Higher values indicated relatively poor coordination or motor control. To measure coordination or motor control with respect to the metronome, relative phase \(\phi_{SD Met}\) was calculated as the difference between the left phase and a sine wave representing the metronome (right phase was used for right ankle trials). Values for \(\phi_{SD}\) and \(\phi_{SD Met}\) were in the approximate range of 10 deg to 100 deg, with values close to zero indicating excellent coordination and values over 80 deg indicating essentially no coordination or relation between the ankles (\(\phi_{SD}\)) or between the ankle and metronome (\(\phi_{SD Met}\)).

To illustrate the concept of relative phase, Figure 2 shows movement angle (range of motion) and relative phase for a subject in each group performing in-phase and antiphase movements in the slow metronome condition (movement frequency 0.5 Hz). From the left, column 1 shows a subject WD performing in-phase movements (intended relative phase = 0 deg), and column 2 shows the same subject WD performing antiphase movements (intended relative phase = 180 deg). Columns 3 and 4 show a subject with CP performing in-phase and antiphase movements, respectively. Rows 1 and 2 show dorsiflexion and plantar flexion angles for the right and left ankle, respectively (range of motion data were centered by subtracting the mean dorsiflexion–plantar flexion angle for the trial). The bottom row shows the relative phase calculated from the right and left ankle movements, calculated as described above. The captions in the bottom row indicate the mean (m) and standard deviation (sd) relative phase calculated for the trial.

Statistical Analysis

The key values from the motor control analysis were \(\phi_{SD}\) and \(\phi_{SD Met}\) \((\pi\) represents 180°). Groups were compared using a mixed design 3-way ANOVA of \(\phi_{SD}\) com-
Results

The interaction of group and phase was significant ($p < .001$; Table 1). The effects of group and phase were significant ($p < .0001$ for both), but the effect of pace was marginally nonsignificant ($p = .053$). Figure 3 shows in-phase and antiphase $\phi_{SD}$ for each group, averaged over movement frequency. Persons in the CP group had larger values for the relative phase measure ($\phi_{SD}$) than persons in the WD group. Both groups had a significantly greater relative phase values for the antiphase movements than the in-phase movements.

The secondary analysis of $\phi_{SD}$ compared WD and CP groups, movement type, and pace indicated significant 3-way interactions ($p < .0001$), group by phase.
The purpose of this investigation was to develop a measure of motor control at the ankle for persons with CP using relative phase. A first step in this development was to quantify differences between persons with CP and those without disability (WD). Four key limitations are associated with this investigation and the discussion must be viewed within the context of these limitations. The first was that data were collected from only 14 subjects with cerebral palsy and 15 without disability. It is possible that the results could change with additional subjects. The second limitation was that a large range of age for the subjects existed. Since it was our initial study, we were able to examine the effects of age on motor control. The third limitation was that the data were collected from only one group of subjects with CP. The final limitation was that the data were collected from only one group of subjects without disability. It is possible that the results would have been different if we had included additional groups of subjects with different levels of disability.

Investigating the results presented in Table 2 yielded no clear interpretation of the 3-way interaction since the results were inconsistent and no trends were evident. Figure 4 shows $\phi_{SD, Met}$ for each phase and group averaged over movement frequency. Persons in the CP group had greater difficulty following the metronome than persons in the WD group as indicated by the larger $\phi_{SD, Met}$ relative phase values relative to the WD group. It should be noted that very few subjects with CP were able to follow the metronome for antiphase trials.

### Table 1  $\phi_{SD}$ (in Degrees) for In-Phase and Antiphase Trials

| Task Pace | In-phase | | Antiphase | |
|-----------|----------|----------|-----------|
|           | WD group | CP group | WD group  | CP group |
| Self-paced| 14.2     | 33.7     | 22.9      | 56.1     |
| 0.5 Hz    | 15.6     | 39.4     | 25.6      | 67.7     |
| 0.75 Hz   | 15.7     | 38.4     | 24.0      | 60.1     |
| 1.0 Hz    | 13.0     | 33.1     | 23.4      | 62.3     |

Figure 3 — In-phase and antiphase $\phi_{SD}$ for each group, averaged over movement frequency (self-paced, 0.5, 0.75, 1.0 Hz). Approximately 7–15 cycles were completed at each frequency for each subject. Standard deviation bars are included and ranged from 4.2 to 4.6. Squares: Cp group. Crosses: WD group.

* Significantly different from WD group ($p<0.05$)

^ Significantly different from Inphase ($p<0.05$)

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Ankle Relative Phase in CP

force over a range of motion (Engsberg et al., 2001). The variables included mean force, standard deviation of the force, and the median frequency of the force. As such, a comparison of variables between studies is impossible. However, the strategies incorporated into each measure are comparable. In fact, our attempts to adapt this “target force” strategy to the ankle led us to the development of the current measure. We found that the children with CP frequently lacked the ability to produce a force great enough to establish a baseline. Relative phase techniques have the advantage of not having a substantial muscular strength requirement for completion, as it is only necessary to overcome the force of gravity to complete the test.

The ankle coordination task in the current experiment was clearly more challenging for the CP group, as they showed overall greater amounts of variability in relative phase ($\phi_{SD Met}$). The third limitation was that only persons with spastic diplegia cerebral palsy (all but 1 subject was GMFCS levels I and II) participated in this study. Thus, extrapolation to other diagnoses (e.g., hemiplegia or quadriplegia) or level of disability (e.g., GMFCS levels IV or V) may not be valid. Finally, the goal of this project was to determine if relative phase might be useful in measuring motor control at the ankle in CP. Usefulness in a clinical setting was not a goal. Future work will consider this issue. For example, a simple, inexpensive electro-goniometer might provide the same information.

Since no other methods have been developed to quantify motor control at the ankle, comparison of the present methods must be confined to other joints. We have previously reported on a measure of motor control at the knee where subjects attempted to match a target

![Figure 4](image-url)

**Figure 4** — $\phi_{SD Met}$ for each phase and group averaged over movement frequency (self-paced, 0.5, 0.75, 1.0 Hz). Approximately 7–15 cycles were completed at each frequency for each subject. Standard deviation bars are included and ranged from 6.1 to 6.6. Squares: Cp group. Crosses: WD group.

<table>
<thead>
<tr>
<th>Task Pace</th>
<th>Left</th>
<th>Right</th>
<th>In-phase</th>
<th>Antiphase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WD group</td>
<td>CP group</td>
<td>WD group</td>
<td>CP group</td>
</tr>
<tr>
<td>0.5 Hz</td>
<td>34.9</td>
<td>65.2</td>
<td>32.6</td>
<td>58.0</td>
</tr>
<tr>
<td>0.75 Hz</td>
<td>30.9</td>
<td>51.0</td>
<td>26.2</td>
<td>64.5</td>
</tr>
<tr>
<td>1.0 Hz</td>
<td>24.1</td>
<td>46.3</td>
<td>24.3</td>
<td>43.3</td>
</tr>
</tbody>
</table>

* Significantly different from WD group (p<0.05)
^ Significantly different from Inphase (p<0.05)
has been observed in bimanual coordination in patients with Parkinson’s disease and children with development.

coordination disorders (Geuze, 2001; Van den Berg, et al., 2000; Volman & Geuze, 1998). These observations indicate that in tasks that emphasize coordination between limbs or limb segments, central deficits as well as existing asymmetries in the neuromuscular actuators due to disease (such as tremor, stiffness, and spasticity) may affect the ability to coordinate the limbs in a regular and systematic fashion (Verheul & Geuze, 2004). In the current experiment, this was the case for the in-phase and antiphase coordination patterns. Although variability of relative phase was greater in both the antiphase and in-phase modes in the CP group as compared with the WD group, antiphase coordination variability was greater than in-phase variability. This difference in coordinate variability is consistent with the literature on bimanual coordination, where greater variability has been observed for the antiphase mode compared with the in-phase mode (Haken et al., 1985).

These differences have been interpreted as the antiphase mode being less stable compared with the in-phase mode, a finding that has also been supported through modeling approaches (Haken et al., 1985). In bimanual coordination, the in-phase mode is established through homologous muscle activation, and the increased stability of this mode of coordination has been attributed to the presence of uncrossed, ipsilateral motor pathways from the motor cortex to the spinal cord (Carson, 2005). Interestingly, in the current experiment, variability in the antiphase mode increased to a greater degree in the CP group as compared with the WD group (significant interaction effect of group × phase; see Figure 2). In a study on bimanual interlimb coordination in Parkinson’s disease patients, Verheul and Geuze (2004) found that more centrally affected patients, showing more symmetrical symptoms, had greater coordination deficits than more peripherally affected patients with more asymmetrical symptoms. The authors interpret these differences in terms of a strong central deficit in which basal ganglia dysfunction may affect the supplementary motor area and pathways underlying interlimb coupling and coordination. Similarly, bilateral thalamic and basal ganglia lesions may affect motor function in CP (Krägeloh-Mann et al., 2002), and disrupt interlimb coordination in this population.

The increased variability in relative phase in ankle coordination in the CP group is also consistent with common observations of increased variability in movement systems due to disease. However, more recent research from dynamical and complex systems perspectives has emphasized the possible functional role of variability (Glass, 2001; Stergiou et al., 2006; Van Emmerik & Van Wegen, 2002). Research on locomotion has indeed shown reversals in the pattern of variability in health and disease. Decreased variability has been observed in the relative phase between the trunk and pelvis as a function of aging and Parkinson’s disease (Van Emmerik et al., 1999, 2005). In individuals with lower extremity pathology due to a variety of orthopedic problems there is a decrease in the within-limb coordination patterns of the lower extremity during locomotion (Barela et al., 2000; Heiderscheit et al., 2002; Kurz et al., 2005). These findings of reduced variability due to pathology have been interpreted as a reduction in the control of the available degrees of freedom in the joints and segments due to disease (Van Emmerik et al., 1999). Changes in variability may also emerge due to a reorganization of the essential control variables underlying the movement task (Latash et al., 2002). Reduced variability in relative phase might impact the ability to change and adapt coordinative patterns when control variables such as movement velocity or frequency are varied (Van Emmerik et al., 1999). The large variability in ankle coordination in the current experiment (observed values were almost double in the CP group) might also impact the ability to control and switch between different coordinative modes. Indeed Kelso and colleagues have shown that in highly asymmetric systems no stable coordinative modes exist, with large variations in coordinative patterns (Kelso & Jeka, 1992). It could be speculated that in cerebral palsy the difficulty in switching between different coordinative modes could greatly affect gait and other movement patterns. In gait, for example, this could mean problems with stopping, starting, or changing speeds, or achieving a rhythmical pattern. Additional work is needed to further understand these issues.

The pacing manipulation did not systematically change the variability of the relative phase between the ankles. This finding is in contrast to the observations in bimanual coordination experiments. When started in the antiphase mode, increases in movement frequency typically result in an increase in relative phase variability before a transition to in-phase coordination. However, the lack of change in variability between the ankles when movement frequency was increased is consistent with earlier results from Kelso and Jeka (1992). These authors found no transitions in the coordination between the left and right leg during a seated multilimb coordination task, possibly due to strong coupling between the legs. In the current experiment there was no increase in relative phase variability between the ankles in both the WD and CP groups. This finding indicates that there was no destabilization of the coordination with higher frequencies in either group at the speeds that were tested.

It should be noted that ROM was not controlled in this study. Observed ROM could be calculated from existing data for each cycle within each time series, but we are not aware of a method that would integrate these data into the measure of relative phase or its standard deviation. Anecdotally, we observed that subjects in both groups, CP and WD, failed to use their maximum ROM for most if not every cycle of each trial. Maximum ROM only makes sense for slow, deliberate motions. When performing a cyclic task at moderate and greater speeds, using maximum ROM would risk discomfort if not injury. To take a broader example,
imagine trying to walk by using one’s greatest possible stride length for each step. In addition, as frequency of movement increased, there may have been a greater failure to follow the metronome pace. Compliance with the metronome was not directly analyzed. Standard deviation of the metronome relative phase was analyzed to partially address this issue. It is possible that cycle-by-cycle variation in ROM and noncompliance with the metronome movement frequency were confounding factors.

The pacing manipulation did have an effect on the deviation from the intended pacing ($\phi_{\text{m}}$) in the CP group. In the antiphase coordination mode, the pattern showing the largest variability in the CP group, large reductions in deviation from intended pacing were observed at higher pacing frequencies (Table 2). This finding is similar to observations of reduced relative phase variability in the relative phase between the left and right leg during locomotion with increasing walking speeds (Wagenaar & Van Emmerik, 2000). These results suggest that, in contrast to common clinical strategies, intervention strategies aimed at making individuals operate at frequencies or speeds greater than preferred may have a beneficial impact on stability of movement coordination.

The results of the present investigation add to the body of knowledge in at least two ways. The first is the demonstration of using relative phase as a measure of motor control at the ankle in CP. Our previous efforts to apply our measure of motor control at the knee in CP (Engsberg et al., 2001) were unsuccessful primarily due to ankle weakness. The children were often unable to produce an adequate force through a range of motion. The use of relative phase only requires the child to overcome the force of gravity during dorsiflexion, and does not require any added force production during the movements. The second addition to the body of knowledge was the quantification of the differences between the group with cerebral palsy and the group without disability. Such a demonstration is a key step in determining the suitability of the measure for quantifying motor control. Future work will determine the sensitivity of relative phase measure in detecting changes due to an intervention, as well as determining its reliability.

The clinical significance of this preliminary study involves the use of this measure as an assessment, outcome, and prediction tool. For example, it is possible that the measure could enhance the GMFCS by further delineating abilities, particularly with children in GMFCS levels 3 and 4 where large variation in ambulatory skill exists. It is also possible that effectiveness of an intervention could be better interpreted, in terms of impairment, with the quantification of changes in ankle motor control. Relative to prediction, with the addition of this ankle measure, we are now in a position to use our three motor control measures (ankle, knee (Engsberg et al., 2001), movement synergy, (Olree et al., 2000)) in conjunction with our spasticity (e.g., Engsberg et al., 1996) and strength (e.g., Engsberg et al., 1998) measures to better predict the functional outcome (i.e., gait speed and GMFM) of children undergoing a selective dorsal rhizotomy (Engsberg et al., 2007). If successful, with the prediction, the process of selecting appropriate candidates for the rhizotomy could be improved. A similar prediction strategy might also be possible with other interventions.

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References


