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Variability and symmetry of gait in early walkers with and without bilateral cerebral palsy

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Abstract

Purpose—Investigating gait characteristics during the early stages of walking in CP may contribute to the understanding of the development of impaired gait. The objective of this study was to investigate differences in the variability and symmetry of spatiotemporal gait characteristics during the early years of walking in children with bilateral spastic CP compared to children with similar amounts of walking experience and typical development (TD).

Methods—The spatiotemporal gait parameters of 31 children (15 with spastic CP, 16 with TD) who had an average of 28.5 (18.1 SD) months of walking experience were collected using an instrumented walkway.

Results—All primary spatiotemporal parameters were reduced in the CP group, who also demonstrated greater stride-to-stride variability, compared to the TD group. There were no statistically significant differences in side-to-side symmetry between groups. Ankle dorsiflexion range of motion was related to several of the gait measures.

Implications—Clinical trials investigating gait interventions during the early years of walking in children with CP should be conducted to determine if treatment can reduce the functional limitations that are present during the emergence of walking skills. Further investigation should examine variability and symmetry in the kinematics, kinetics, and muscle activity patterns of early walkers with CP, and the effect of treatment on the variability and symmetry of walking characteristics.

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Keywords

cerebral palsy; gait; variability; symmetry; early walking

Cerebral palsy (CP) is characterized by impairments in the development of movement and posture that are attributed to disturbances that occurred in the developing fetal or infant brain.[1] Movement impairments specific to walking have been reported in numerous studies in individuals with CP.[2-4] However, there has been no investigation that has specifically reported the gait impairments that are present during the early years of walking in CP.

To aid development of appropriate treatment programs for young children, it is important to examine gait patterns during the development of impaired walking patterns. Measurement of the characteristics of gait during the early years of walking may provide insight into potential strategies to treat or prevent gait impairments in CP. The majority of gait research in CP includes participants who are between the ages of five years and adolescence, which are many years after the onset of walking. Young children are rarely included as research participants, in part because of limited attention, cognition, and tolerance to the instrumentation involved in gait analysis.

The immaturity of movement patterns in early walkers also complicates data interpretation. Mature gait is characterized by low variability[5] and a high degree of symmetry[6] from stride-to-stride, but children have greater stride-to-stride variability than adults.[7] The variability and symmetry of gait should be reported for young children with CP to further characterize immature walking patterns.

To better understand the process of the development of impaired gait patterns in CP, walking should be studied from the onset of skill development rather than by chronological age. The objective of this study was to investigate differences in spatiotemporal gait characteristics during the early stages of walking in children with bilateral spastic CP compared to children with similar amounts of walking experience and typical development (TD). In addition, the variability and symmetry of these measures, and their relationships with musculoskeletal measures, were investigated.

Methods

Participants

Participants with CP were recruited through our institution's outpatient clinic and other area rehabilitation facilities. Participants with TD were recruited from siblings of the participants with CP, children of people known to the investigators, and a local day care. A university institutional review board approved all procedures. Parents gave informed consent to the research and publication of the results. Assent of a minor was also obtained from participants seven years of age or older.

Inclusion and exclusion criteria are listed in Table 1. Children with CP were able to walk with a hand-held assistive device if it did not restrict movement of the trunk or pelvis. The selection of walking experience rather than age as a primary inclusion criterion was chosen based on reports that experience is a stronger predictor of walking and balance skill than age in early walkers.[8, 9] The onset of walking was operationally defined as the age in months at which a child was able to take at least three continuous independent steps.[10] Walking experience, in months, was calculated as the difference between the participant's age on the day of the study and at onset of walking. This is a novel approach for CP research because the majority of investigations compare children with CP to children with TD who are the same age, rather

comparing groups who have similar amounts of walking experience, despite later onset of walking in CP.

Procedures

Musculoskeletal measurement—All anthropometric and musculoskeletal measurements were taken by one pediatric physical therapist. The anthropometric measures included height, seated height, weight, and bilateral leg length. All distances were measured with a Harpenden anthropometer (Holtain Limited, Pembrokeshire, UK) except in two cases when a cloth tape measure was used because the children were fearful of the device.

Range of motion (ROM) measures in children with CP included bilateral hip extension, hamstring length, and ankle dorsiflexion. Hip extension was measured using the Thomas test method and hamstring length was measured using the popliteal angle method.[11] Ankle dorsiflexion was measured in prone with the knee extended. Muscle stiffness was measured bilaterally in the hamstrings and hip adductors in children with CP using the modified Tardieu scale.[12] As described by Yam and Leung,[13] R1 was the angle at which a change in muscle resistance, or “catch”, was detected when the limb was moved at a fast velocity, R2 was the end range of the muscle length, and *X* was recorded as the quality of the muscle reaction.[13] The children were able to watch a video or play with a research assistant during the musculoskeletal examination to increase tolerance and compliance.

Walking trials—Children walked barefoot down an instrumented walkway (GAITRite®, CIR Systems, Havertown, PA, USA) at a self-selected pace. Three to five trials, each consisting of one walk down the walkway with at least four consecutive footfalls, were collected depending on participant tolerance. Footfall information was collected at 30 Hz.

Start and stop targets were placed on the floor approximately five feet beyond either end of the walkway to minimize acceleration or deceleration during the walking trials. A walking trial commenced by having the child stand on the start target. Data collection was initiated through the GAITRite® software and the child was instructed to walk to the target beyond the opposite end of the walkway. Children had the opportunity to sit between walking trials to minimize fatigue. All walking trials were videotaped for later gait cycle selection and parents/caregivers signed a separate consent to allow videography.

Data analysis

Five gait cycles for each side (left and right) were selected based on the observation of each individual's typical walking (child was not distracted, did not stop walking, and was not reaching arms toward an object). Individual footfall data generated by the GAITRITE® analysis software for these strides were used for analysis. Four primary spatiotemporal parameters were analyzed: walking velocity, cadence, step length, and single support time (as a percent of the gait cycle). For all measures except single support time, the 10 gait cycles were averaged to calculate the main parameter value. For single support time, left and right sides were added, then averaged, to represent the total time on any one limb during the entire gait cycle. Step length and walking velocity were normalized to leg length and converted to dimensionless values.[14]

Individual means and stride-to-stride measures of variability (standard deviations (SD), coefficients of variation (CV)) were calculated for each parameter by averaging the 10 values from the individual gait cycles. The CV can be more meaningful than the SD as a measure of variability when there is the potential for large differences in group means.[15] In addition, a symmetry ratio was calculated for each parameter by dividing the smaller left or right value

by the larger value. This resulted in a value between 0.0 and 1.0, with values closer to 1.0 indicating greater symmetry.

Group means and 95% confidence intervals were then calculated for each parameter, and each variability and symmetry measure. Due to unequal variance between groups and non-normal distribution of the data, a general linear model (GLM) was used to determine differences in spatiotemporal measures. Group differences in walking experience and anthropometric measures were examined using t-tests and considered covariates in the GLM if different ($p<0.05$). Linear regressions and the corresponding coefficients of determination (R^2) were used to account for the variance in spatiotemporal parameters in the CP group explained by ROM and spasticity measures.

Results

Thirty-four children enrolled in this study. Data from three children were excluded due to one having a questionable diagnosis of CP, and two who were unable to walk without additional assistance from an investigator during the testing session. Data for the remaining 31 children were used for analysis. In the group of children with CP, seven were classified as GMFCS level II and eight were level III. One was classified as quadriplegic, and 14 as diplegic. Three walked without assistive devices, nine used posterior rolling walkers, one used bilateral forearm crutches, and two used unilateral forearm crutches. ROM data were not obtained from one child due to time constraints. Demographic and musculoskeletal data are provided in Tables 2 and 3, respectively.

Walking experience did not differ between groups ($p=0.969$). However, because the onset of walking was later in the CP group, they were older than the TD group, and were larger in some anthropometric measures. Height, body mass index, and seated height did not differ between groups ($p=0.080$, 0.102, 0.601, respectively). The CP group was heavier ($p=0.017$) and had longer legs ($p=0.029$) than the TD group. Weight was, therefore, used as a covariate for the GLM for comparison of all spatiotemporal measures. Leg length was used as a covariate for cadence and single support measures (walking velocity and step length were normalized to leg length prior to statistical analysis).

Group means for the primary spatiotemporal parameters, the stride-to-stride variability measures (SD, CV), and the symmetry ratios are presented in Table 4. Means were significantly lower in the CP group than the TD group for all main parameters: walking velocity, cadence, step length, and single support time. Stride-to-stride CVs were significantly higher in the CP versus TD group for cadence and single support. The stride-to-stride SDs were also higher for single support time. Symmetry ratios were not different between the TD and CP groups for any spatiotemporal measure.

Only two of the spatiotemporal measures were related to musculoskeletal measures in the CP group. Increased average ankle dorsiflexion ROM was related to decreased step length ($p=0.042$) and increased cadence variability ($p=0.023$). Hip extension and hamstring ROM were not related to any of the spatiotemporal measures. Similarly, Tardieu test R1, R2, and *X* values for both hamstrings and adductors were not related to any of the spatiotemporal measures. Table 3 presents the significant relationships ($p<0.05$) between musculoskeletal and spatiotemporal measures.

Discussion

This study investigated differences in spatiotemporal characteristics of gait, and the variability and symmetry of these measures, during the early years of walking in children with CP and TD. Children with CP achieved independent walking at a later age than those with TD. The

method of using walking experience, rather than age, for inclusion in the study controlled for the maturation of walking ability that occurs with practice after the onset of walking. Because of delayed motor development in individuals with CP, however, there were some body size differences between groups (children with CP were bigger) which were accounted for during analysis of the data.

Children with CP demonstrated slower walking velocity, decreased cadence, shorter step length, and reduced single limb support compared to children with TD. Spatiotemporal gait parameters for the TD group were consistent with normative values previously reported.[16-18] Spatiotemporal parameters for the CP group were slightly lower than those reported by Wondra and colleagues for a group of children with mixed motor disabilities.[19] However, the children in that study were an average of 1.5 years older and the sample was more heterogeneous (including children with diplegia, hemiplegia, ataxia, Angelman syndrome, and arthrogryposis) than the sample in the present study. Walking speed in the current study was also less, approximately half, than that reported by Sorsdahl and colleagues[22] for a group of children with CP, but who were less impaired than the current sample. None of the children in Sorsdahl's study walked with an assistive device and all were classified as GMFCS I or II.

Stride-to-stride variability was significantly higher in the CP versus TD group for cadence (CV) and single support (SD, CV). To our knowledge, stride-to-stride variability data for spatiotemporal gait measures is limited for typically developing children and has not been reported for children with CP. Hausdorff and colleagues found that stride time is more variable in 3-4 year old children compared to 6-7 year old children, who demonstrate more variability than 11-14 year old children.[5] However, these investigators did not report any of the parameters measured in our current study. Looper and colleagues reported a CV for step length of 0.38 in nine new walkers with TD.[20] In our study, the mean step length CV was 0.11, but our participants had more walking experience, which may partially explain the observations of lower variability.

Although the values were lower and the ranges were wider in the CP group, the symmetry ratios for all parameters were not statistically different between the TD and CP groups. Side-to-side symmetry has not been previously reported for spatiotemporal gait parameters in children with bilateral CP. The symmetry ratios for our TD group ranged from 0.92 to 0.95. This is lower than the values reported by Wheelwright and colleagues for step length and swing time in children (median 0.99 for both), and similar to the median symmetry ratio for double support time (0.91).[21] The sample in Wheelwright's work was older, consisting of 134 children aged 3-18 years, and thus would be expected to have greater symmetry than the TD children in the present study. Another study also supports the notion of greater side-to-side symmetry for adolescents compared to children.[22]

Only step length and variability in cadence were related to musculoskeletal measures in the CP group. Spasticity was not related to any of the spatiotemporal measures, which is consistent with the findings of Ross and Engsberg.[23] Some of the spatiotemporal parameters were related to lower extremity ROM. Greater dorsiflexion range was associated with greater variability in cadence and shorter step length. The maximal range of ankle dorsiflexion in the CP group (demonstrated by two older children) exceeded typical dorsiflexion values in children, suggesting that excessive dorsiflexion range combined with the other impairments observed in CP is one factor that may contribute negatively to walking ability.[24]

Children with CP demonstrated reduced walking ability during the early stages of walking even when walking experience was matched between groups. These differences are consistent with those seen in older children with CP, confirming that the spatiotemporal gait impairments observed in CP are present early after the onset of walking. Gait variability is increased in

children[7] and in elderly adults who have poor motor control.[25] The increased stride-to-stride variability in the early walkers with CP in this study may suggest that separate from potential underlying muscle weakness, the neural circuitry supporting these gait patterns is not yet well-established and may be affected favorably with intervention. Although the majority of young children with CP receive early intervention therapy services that may include gait and postural training, publication of systematic training approaches with clearly defined outcomes of these services on walking ability is limited. Clinical trials investigating gait interventions during the early years of walking in children with CP should be conducted to determine if treatment reduces the functional limitations that are present during the emergence of walking skills.

The participants in this study were a fairly homogeneous group of children with bilateral spastic CP, GMFCS II and III. These results may not be generalizable to children with greater walking experience, unilateral CP, or those with greater or lesser ambulatory ability. In addition, it is important to consider that although the groups had equal time since the onset of walking (walking experience), the amount of walking practice was still likely to be higher in the TD group. After the onset of walking, walking quickly becomes the primary means of mobility for children with TD, but children with CP often practice walking only in therapy sessions or during more structured periods of practice at home.

Conclusion

Differences were present in the walking performance of children with bilateral spastic CP compared to children with TD during the early stages of walking ability, even when children were grouped by walking experience rather than age. Well defined gait training interventions with measureable and objective outcomes should be reported to determine if treatment can reduce the functional limitations that are present during the early years of walking in children with CP. Future investigation should examine treatment programs delivered during the early years of walking, and study the development of compensatory gait patterns through longitudinal studies, including the use of physical activity measures to quantify walking “practice” in young children with and without CP. Additionally, future work should examine the variability and symmetry in other early walking characteristics, such as kinematics, kinetics, and muscle activation patterns.

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Table 1

Participant inclusion and exclusion criteria.

Inclusion	Exclusion
• 0.5-60 months of walking experience • Able to ambulate barefoot at least 15 feet in a forward direction with supervision (children with CP could use an assistive device) • Able to follow 1-step verbal instructions For children with CP only: • Bilateral spastic CP (diplegia or quadriplegia) • GMFCS II-III classification[30]	• Lower extremity bony or soft tissue surgery or fracture in the past 12 months For TD children only: • History of any orthopedic, neuromuscular, or cardiovascular condition For children with CP only: • Spastic hemiplegic or non-spastic classification • History of dorsal rhizotomy • History of tendon transfer to a target muscle • Botulinum toxin injection to a lower extremity muscle in the past 6 months • Secondary orthopedic, neuromuscular or cardiovascular condition

Table 2

Demographic and anthropometric data.

		Number (n)	Onset of walking (months)	Walking experience (months)	Gender	Age (months)	Weight (kg)	Height (m)	BMI (kg/m^2)	Seated Height (m)
TD	Mean (SD)	16	11.7 (3.1)	28.6 (19.6)	9F, 7M	39.7 (19.5)	15.1 (3.9)	0.97 (0.13)	15.9 (1.8)	0.55 (0.06)
	Range		8.0-20.0	1.0-58.0		13.0-67.5	10.0-21.9	0.75-1.18	11.2-18.8	0.46-0.69
CP	Mean (SD)	15	34.8 (10.2)	28.4 (17.0)	5F, 10M	63.1 (23.2)	19.6 (5.9)	1.06 (0.14)	17.2 (2.4)	0.56 (0.06)
	Range		18.0-55.0	2.0-60.0		25.0-108.0	10.9-31.2	0.83-1.32	14.7-22.9	0.48-0.65
Total	Mean (SD)	31	22.9 (13.8)	28.5 (18.1)	14F, 17M	51.0 (24.1)	17.3 (5.4)	1.10 (0.14)	16.5 (2.2)	0.56 (0.06)
	Range		8.0-55.0	1.0-60.0		13.0-108.0	10.0-31.2	0.75-1.32	11.2-22.9	0.46-0.69

TD=typically developing, CP=cerebral palsy, SD=standard deviation, M=male, F=female, kg=kilograms, m=meters, BMI=body mass index

Table 3

Musculoskeletal measures and significant relationships between musculoskeletal and spatiotemporal measures for individuals with CP.

Musculoskeletal measure		Mean (SD)*	Range*	Spatiotemporal measure	r	R^2	*p* value
Hip extension ROM		-2 (2)	-9-0	none	n/a	n/a	n/a
Dorsiflexion ROM		7 (9)	-5-27	cadence CV	0.602	0.363	0.023
				step length	0.548	0.301	-0.042
Hamstrings ROM		133 (9)	118-150	none	n/a	n/a	n/a
Hip adductor spasticity	R1	17 (8)	2-33	none			
	R2	31 (12)	15-62	none	n/a	n/a	n/a
	X	1.7 (0.4)	0.5-2	none			
Hamstrings spasticity	R1	94 (10)	68-109	none			
	R2	133 (9)	118-150	none	n/a	n/a	n/a
	X	1.9 (0.2)	1.5-2	none			

SD=standard deviation, ROM=range of motion, CV=coefficient of variation,

* average of left and right sides, measured in degrees except for *X* value

Table 4

Group means (and 95% confidence intervals) for spatiotemporal parameters, stride-to-stride variability, and symmetry.

Spatiotemporal measure	Stride-to-stride variability									Symmetry ratio		
				SD			CV					
	TD	CP	*p* value	TD	CP	*p* value	TD	CP	*p* value	TD	CP	*p* value
Walking velocity^	0.42 (0.38-0.45)	0.22 (0.16-0.28)	<0.001*	0.05 (0.03-0.07)	0.06 (0.04-0.08)	0.611	0.01 (0.01-0.02)	0.03 (0.01-0.05)	0.082	0.93 (0.90-0.97)	0.78 (0.62-0.95)	0.091
Cadence (steps/min)	155.2 (144.7-65.7)	103.3 (83.3-123.4)	0.001*	14.3 (10.5-18.1)	21.7 (10.9-32.5)	0.194	0.09 (0.07-0.11)	0.21 (0.13-0.29)	0.019*	0.95 (0.93-0.97)	0.87 (0.79-0.96)	0.153
Step length^	0.76 (0.72-0.79)	0.55 (0.46-0.64)	0.001*	0.08 (0.05-0.10)	0.12 (0.08-0.16)	0.074	0.11 (0.07-0.14)	0.26 (0.05-0.46)	0.222	0.93 (0.90-0.96)	0.83 (0.68-0.99)	0.266
Single support (% gait cycle)	84.8 (83.3-86.2)	77.5 (70.4-84.5)	0.049*	4.1 (2.7-5.4)	10.4 (5.0-15.8)	0.021*	0.05 (0.03-0.06)	0.16 (0.07-0.25)	0.018*	0.95 (0.93-0.97)	0.85 (0.77-0.92)	0.077

TD: typically developing, CP: cerebral palsy, SD: standard deviation, CV: coefficient of variation

^walking velocity and step length are dimensionless values, normalized to leg length

*indicates significant difference ($p<0.05$)