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A cross sectional study investigating dynamic balance when stepping to targets in children with cerebral palsy compared to typically developing children

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Highlights

• Children with cerebral palsy have significantly greater stepping error when stepping to a target than typically developing children

• Children with cerebral palsy show smaller medio-lateral anticipatory postural adjustments

• Children with cerebral palsy show greater difficulty stepping to a medially placed target

• Medio-lateral anticipatory postural adjustments may be limited by proximal muscle strength and gastrocnemius length

• Limited gastrocnemius range affects antero-posterior motion when stepping with the contralateral leg.

ABSTRACT

Background

Children with Cerebral Palsy (CP) have altered anticipatory postural adjustments (APAs) during gait initiation. These APAs may affect dynamic balance in tasks such as stepping.

Research Questions

How are APAs in children with CP affected during stepping to precise targets? How do children with CP modulate APAs when stepping to medial and lateral targets? What is the association between APAs and symptom severity, movement quality and impairment profile?

Method

Children undertook a stepping task to laterally and medially placed targets with either leg, in a randomised order. Movement of the centre of pressure (COP) and markers at the pelvis and foot were measured via a force plate and 3D motion analysis. Motion of the centre of mass (COM) was estimated via pelvic markers. APAs were assessed prior to leading leg lift-off in medio-lateral and antero-posterior directions. Stepping error was calculated. Baseline characteristics of children with CP included Gross Motor Function Measure (GMFM), Quality Function Measure (QFM), leg muscle hypertonia (Tardieu test) and strength (manual dynamometry).

Results

Sixteen ambulant children with CP (12.2 years ± 2.2) and 14 typically developing (TD) children (11.6 years ± 2.9) were assessed. In children with CP, APAs in the medio-lateral direction were 20-30% smaller. Children with CP were less able to modulate their APAs with steps to medial and laterally placed targets, than TD children. Medio-lateral COP motion was associated with movement quality assessed by QFM subsections, GMFM (correlation coefficient r =0.66-0.80) and hip abductor strength (r=0.75). Antero-posterior APAs were significantly smaller when stepping with the non-paretic leg in children with CP. APA size was positively related to the length of the contralateral, paretic gastrocnemius (r=0.77). Stepping error was higher in children with CP and inversely correlated to the size of the medio-lateral APA.

Conclusion

Children with CP show smaller medio-lateral APAs especially when stepping to medially placed targets. APA size may be limited by proximal muscle strength and gastrocnemius length.

INTRODUCTION

Cerebral Palsy (CP) is associated with deficits in posture and balance that affect children's ability to perform the functional activities (1). Dynamic balance is essential for tasks such as stepping over a toy or manoeuvring in a confined space, such as a shower cubicle. Dynamic balance requires the controlled movement of the centre of mass (COM) within the base of support (2). It involves a preparatory phase, where anticipatory postural adjustments (APAs) prepare the body for the execution phase when the leg is brought forward to its intended target (3, 4). Dynamic balance while taking a single step has been modelled as a 'throw and catch' of the COM (5, 6). This consists of APAs that accurately 'throws' the COM on a ballistic trajectory initially towards the trailing leg and then forwards towards the leading leg (4). The motion of the body and the stepping leg are coordinated with the COM motion varying with stance width and the position of the stepped foot (7). Therefore, dynamic balance consists of accurate control and modulation of APAs to control the subsequent trajectory of the body during single leg stance and the positioning of the limb receiving the COM.

Previous work on gait initiation reveals notable differences in APAs related to the severity and laterality of CP (8, 9). Children with unilateral CP tend to have reduced medio-lateral movement of the COM and children with bilateral CP have an increased downward shifting of the body prior to initiating gait. In children with unilateral CP, the COM moves forward less efficiently when the affected leg is trailing (9). However, while this work explores gait initiation, it is unclear how these altered APAs might affect dynamic balance while taking a single step to a precise target. We do not yet know how children with CP modulate APAs according to the target step's location. The motor impairments affecting balance in children with CP include spasticity, contracture, weakness and reduced selective movement (3, 10).It is unknown how APAs associated with stepping to a target vary according to the severity of these impairments.

Aims and Objectives

This study aims to compare dynamic balance, while stepping to medially and laterally placed targets, in children with CP and TD. The objectives are to assess the APAs by measuring the COP, COM estimate (COM_{est}), and stepping accuracy in a group of children with CP and TD. We will test the hypothesis that APAs will be smaller in children with CP, will be associated with reduced stepping accuracy and show a significant relationship with participants' impairment profile.

METHOD

A cross-sectional design assessed children on a standardised stepping task.

Participants

Paediatric physiotherapists working in five child development centres in the South West of England recruited children with CP. Children (aged 8-18 years) were eligible if they had a diagnosis of CP, Gross Motor Function Classification System (GMFCS) levels I-III (11), and were able to stand and take up to five steps in bare feet without holding onto equipment. Children were ineligible if they had additional diagnoses affecting balance, were unable to follow complex instructions or were unable to see the

illuminated markers on the floor. Using local adverts, we recruited TD children who had no conditions that affected balance or movement.

Sample Size

Previous comparisons of movements of sacral markers as motion of COM_{est} have found differences in COM APA vertical motion between children with CP while stepping (unilateral 26.18mm (±9.11), bilateral 18.08mm (±18.09) and TD 34.31mm (±8.63)) (8). This produced an average effect size of 1.1. To detect a similar effect size (α=0.05, power=90%) would require a sample size of 30 participants.

Procedures

Participant demographics and impairment profile were assessed. Contractures and spasticity of hamstrings (popliteal angle), rectus femoris (Duncan Ely) and gastrocnemius (dorsiflexion with knee extended) were measured using goniometry and the Modified Tardieu Scale (12). Isometric strength of hip and knee extensors and hip abductors were assessed using a hand-held dynamometer (Lafayette, USA) in standardised positions. The product of the recorded Force x Distance from the point of force application to joint axis provided a measure of the Joint Moment [14, 15]. Gross Motor Function Measure (GMFM) (13) and Quality Functional Measure (QFM) (14) was also determined for children with CP.

Children wore shorts, top, and were barefooted. Children with a leg length shorter than 87cm (measured from the anterior superior iliac spine (ASIS) of the pelvis to the medial malleolus) used stepping targets set at 26cm and children with leg length longer than 87cm used targets set at 35cm. Both target distances were deemed comfortable in pilot studies with TD children. Children stood on a black cardboard platform that housed four targets, which overlaid an embedded portable force plate (Kistler™ 9286BA UK, **Error! Reference source not found.**. The targets consisted of a 2cm diameter circle made of electroluminescent paper. The children stood with their 1st metatarsal-phalangeal joint (MTP) joints 4cm apart. The targets were directly in front (medial target) or 25° to the side (lateral target) for each foot (Figure 1A). Both medial targets overlaid the force plate. Participants had four CODAmotion™ (Leicestershire, UK) electronic markers on each foot, placed at the head of talus, 1st and 5th MTP and on nail of the great toe. A cluster of three markers were placed on a Velcro belt, positioned on a line horizontal with the ASIS's, with the central marker aligned with the midline of the child's body. They were able to hold onto a walking frame/ parallel bars, as needed, when determining the starting position and at the end of a trial when repositioning the foot.

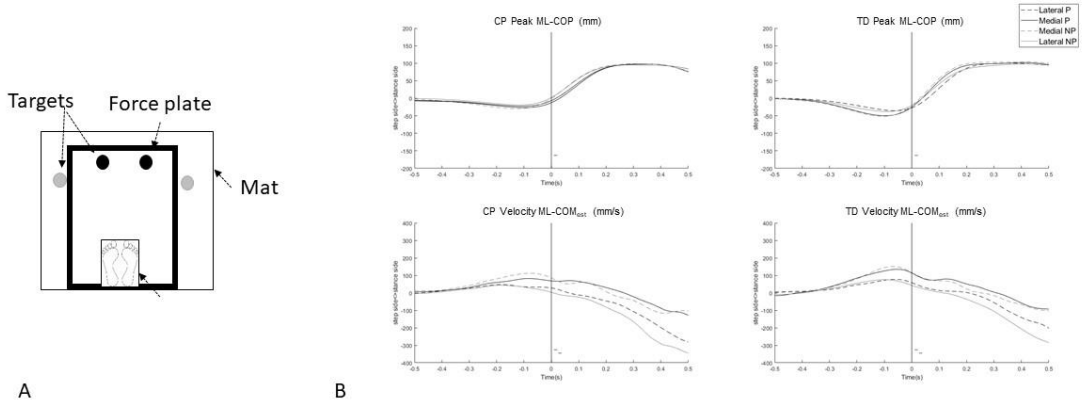

Figure 1

A Experimental set up showing target location relative to force plate.

B Grand average response of medio-lateral centre of pressure (ML-COP (top))and the centre of mass estimate (COM_{est} (bottom)) for children with cerebral palsy (CP (left)) and typical development (TD (right)).

To allow a consistent measure of stepping accuracy, the child was asked to practice stepping their leading foot as accurately as possible onto each target, without rushing, and bring their second foot alongside. This 'best step' target step position was then marked by chalking around the child's leading foot and the position of the leading foot recorded using the 3D motion analysis system (see below) to allow for a calculation of absolute stepping error relative to this position.

The onset of a stepping trial was indicated by a tone whose pitch (high or low) indicated which leg to step with whilst the target simultaneously illuminated. The child was asked to undertake up to four sets of 15 steps with breaks in between sets. This allowed a maximum of 15 trials to each target to be recorded.

Movement data were sampled at 200Hz using the CODAmotion™ minihub and stored using CODAmotion™ software (Leicestershire, UK). Force plate data were sampled at 200 Hz via a power 1401 analogue-digital converter (CED Cambridge UK) and stored using Signal software (CED Cambridge UK). The motion analysis and force plate data were synchronised via transistor-transistor logic pulses generated by the onset of CODAmotion data analysis.

A 0.5-1.5 second random delay occurred between the onset of recording and the onset of the target light/auditory tone. This allowed the collection of baseline data whilst the random delay prevented the child from anticipating the onset of the target.

Data Reduction

Data were exported as text files for secondary analysis in MATLAB™ (Mathworks USA). Target indicator and force plate data were combined with CODAmotion data and grouped according to the target. Data were omitted from all analyses where there was marker drop out. The onset and off set of stepping was automatically determined from the vertical acceleration of the centroid of the foot markers (15) based on data rising above and below the mean baseline level for at least 125ms. If there was an acceleration deviation in a 200ms period after foot offset, this indicated a shuffle in the leading foot and data were rejected. This accounted for ~5% of records and was similar in children with CP and TD children.

Four APAs were calculated in the 500ms period prior to the onset of stepping with the leading leg: peak medio-lateral (ML), antero-posterior (AP) motion of the COP, ML and AP velocity of the COM estimate (COM_{est}). The peak ML-COP and the peak AP-COP motion in the direction of the leading leg was calculated relative to the baseline period. The midpoint of the ASIS markers was used to calculate the ML and AP velocity of COM_{est} in the direction of the trailing relative to the baseline. The fifth outcome was calculated over the 200ms period after foot offset. The accuracy of the end foot position was defined as the endpoint step error to the 'best' foot position target. This was calculated as the absolute distance between the centroid of the foot (defined from the three markers) and the centroid of the target (defined as the centroid of the 'best step' taken at the start of the trial).

Statistical Analysis

Data were arranged as if children were stepping to the left side by inverting the ML related data. Further, the more paretic leg (termed paretic) was compared to stepping with the less paretic leg (termed non-paretic). For TD children the weaker leg was grouped with the paretic leg and the stronger leg with the non-paretic side. Leg strength was determined using the mean of the isometric strength measures. For children with CP and hemiplegia the paretic leg corresponded to the clinical diagnosis with the non-involved side termed the non-paretic leg. Two (out of 6) children with diplegia had a weaker left leg. Seven out of 14 TD children had a weaker left side

Data were assessed for normality using a Shapiro-Wilks test. Data were normally distributed except for AP-COP, AP-COM_{est} and stepping error measures. Differences in demographics and clinical measures between the two groups were compared using an unpaired t-test. Differences between groups (TD vs CP) for the movement-related variables (ML-COP and COM_{est}) were compared using a between groups repeated measures ANOVA with factors leg (left or right) and target (medial or lateral). For non-normally distributed data, group responses (AP-COP and AP-$COM_{est,}$ and stepping error) to steps to each target were compared using a Mann Whitney test.

In children with CP, the differences in the mean ML-COP according to GMFCS level (1 vs 2) were compared using unpaired t-tests. Further, in children with CP, a Pearson Correlation coefficient assessed the correlation between mean ML-COP and GMFM walk and stand scores, Quality Function Measure sub scores (QFM) and selected measures of the child's level of impairment (Hamstring R1 and R2; Gastrocnemius R1 and R2 and Knee extensor strength and Hip abductor strength). A

Bonferroni correction was used for multiple comparisons (n=7 GMFM & QFM measures, n=12 for measures of range of motion and n=6 for measures of strength). Finally, based on previous work (9) the relationship between AP-COP peak when stepping with either leg and the contralateral gastrocnemius passive range was explored.

Permission for this study was granted by South West Frenchay Research Ethics Committee (ref 18/SW/0239). The study is reported according to STROBE guidelines (16).

RESULTS

Participant characteristics and impairment profile

Thirty children were recruited, 14 children with TD (mean age 11.58 years ± 2.91 SD) and 16 children with CP (mean age 12.15 years ± 2.18 SD). The groups had similar gender distribution, weight and height (Table 1). Of the children with CP, six had bilateral CP, (median GMFCS level II, range 1-2). Ten children had unilateral CP; five children had right hemiplegia (median GMFCS level I, range 1-2) and five children had left hemiplegia (median GMFCS level II, range 1-2) (Table 1).

Table 1. Participant demographics

Study Group:	**Typically Developing** n=14	**Cerebral Palsy** n=16
Gender Male (Female)	6 (8)	7 (9)
Age (years, mean ± SD)	11.6 ± 2.9	12.2 ± 2.2
Height (cm, mean ± SD)	152.2 ± 13.3	147.9 ± 13.5
Weight (kg, mean ± SD)	42.7 ± 10.0	43.1 ± 15.3
GMFCS level (I:II:III)	-	7:8:1
Distribution of Impairment Bilateral	-	6
Distribution of Impairment Unilateral Right: Left	-	5:5

Key- Number (N), Gross Motor Function Classification System (GMFCS), mean (M), standard deviation (SD)

Children with CP had significantly reduced passive range in both hamstrings (as measured by popliteal angle) on the paretic side. Spasticity as measured by the modified Tardieu test (R1) was greater in the CP group in the paretic and non-paretic hamstrings (Table 2). Strength was lower in the CP group for the knee flexors and extensors on the paretic side but this was not significant after a Bonferroni correction (Table 2). Table 3 shows that QFM and GMFM walk and stand scores reduced with increasing GMFCS classification in children with CP.

Table 2. Mean measures of leg impairment in children with typical development and cerebral palsy.

Parameter	**Cerebral Palsy n=16**		**Typically Developing n=14**	
	P	*NP*	*P*	NP
Hamstrings R2 (°)	50.8 (10.4) *	42.3 (7.0)*	33.0 (10.3)	29.6(10.2)
Hamstrings R1 (°)	61.4(16.0) *	52.3 (13.6)*	34.8(11.3)	36.7(14.1)
Gastrocnemius R2 (°)	2.6(6.8)	5.3(9.8)	9(5.3)	10.1(4.8)
Gastrocnemius R1 (°)	-4.3(11.1)	-0.5(12.1)	3.9(6.9)	2.5(7.9)
Rectus Femoris R2 (°)	133.4(16.4)	128.3(18.8)	142.9(6.8)	137.2(27.5)
Rectus Femoris R1 (°)	128.1(31.7)	126.4(24.1)	142.5(7.4)	138.3(29.1)
Knee Flexion Moment (Nm)	33.2(13.1)	39.2(16.0)	50.4(25.5)	54.5(29.7)
Knee Extension Moment (Nm)	48.2(19.1)	57.8(27.6)	64.9(16.7)	71.7(19.8)
Hip Abduction Moment (Nm)	41.0(23.0)	43.7(24.8)	56.9(20.6)	59.5(20.4)

Key- Mean and standard deviation (SD) indicated, R1= modified Tardieu scale fast stretch, R2=modified Tardieu scale slow stretch, P=paretic leg, NP=Non-paretic leg,* indicates significant difference between CP and TD group after Bonferroni correction**,** Nm=Newton metres

Table 3. Mean Quality Function Measure and Gross Motor Function Measure scores for children with cerebral palsy

Parameter	**All n=16**	**GMFCS I n=7**	**GMFCS II n=8**	**GMFCS III n=1**
GMFM stand	84.8 (16.4)	93.5(8.9)	84.0 (2.3)	30.8
GMFM walk	79.4(26.6)	95.9(24.4)	72.9(3.3)	15.3
QFM alignment	62.4(19.8)	77.6(11.9)	55.0(10.3)	15.4
QFM co-ordination	67.2(25.3)	84.5(20.6)	59.6(9.0)	7.2
QFM dissociated movement	57.7(23.5)	75.9(17.8)	47.8(9.8)	8.9
QFM stability	63.2(24.5)	80.7(20.5)	54.8(7.4)	7.8
QFM weight shift	61.0(21.4)	78.0(15.3)	51.8(8.1)	15.2

Key- Mean and standard deviation (SD) indicated**,** Gross Motor Function Classification (GMFCS), Gross Motor Function Measure (GMFM), Quality Function Measure (QFM)

APA response characteristics: On average 11.7 ±(2.4) steps to each target were analysed (CP 11.4 ±2.6; TD11.9 ±2.3)**.** The grand average response curves are shown in Figure 1B.

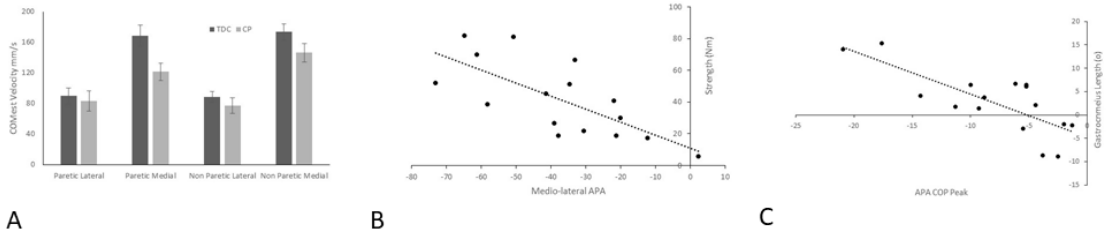

Figure 2

A Difference in medio-lateral centre of mass estimate (ML-COM_{est}) velocity when stepping with the paretic (or weaker for TD) and non-paretic sides to lateral and medial targets.

B Relationship between medio-lateral centre of pressure (ML-COP) peak and mean hip abductor strength. A negative value of ML-COP indicates a greater lateral motion

C Relationship between anterior-posterior centre of pressure (AP-COP) and gastrocnemius length. A more negative COP indicates greater posterior motion.

ML-COP peak: ML-COP peak velocity prior to foot lift of the leading leg (foot-offset) was larger when stepping towards medial compared to lateral targets (Effect of target $F(1, 28) = 15.4$ $p<0.001$, Table 4). ML-COP peak velocity was smaller in the CP group (Effect of Group $F(1, 28) = 9.1$ $p<0.005$) (Table 4, Figure 2A). There were no other significant interaction effects.

Table 4. Anticipatory postural adjustment parameters for children with CP and typically developing children. Mean (standard deviation) indicated.

	Cerebral Palsy				Typically Developing			
	Lateral P	**Medial P**	**Lateral NP**	**Medial NP**	**Lateral P**	**Medial P**	**Lateral NP**	**Medial NP**
Peak ML-COP (mm)	-35.1 6.1)	-38.4 (6.0)	-32.0 (5.0)	-43.7 (6.3)	-48.9 (4.1)	-58.4 (5.1)	-52.3 (3.7)	-67.1 (5.3)
Peak AP-COP (mm)	-8.1 (2.1)	-9.2 (2.7)	-7.1 (1.2)	-8.9 (1.8)	-9.52 (1.5)	-12.8 (1.4)	-10.7 (1.3)	-12.2 (1.9)
Peak ML-COM velocity (mm/s)	83.1 (13.1)	121.5 (11.3)	77.5 (10.2)	146.4 (11.8)	89.8 (10.5)	168.8 (13.7)	88.4 (6.9)	173.5 (10.3)
Peak AP-COM velocity (mm/s)	-68.0 (10.6)	-107.1 (14.8)	-63.9 (10.2)	-102.3 (12.2)	-54.7 (11.7)	-95.0 (16.8)	-65.3 (11.5)	-93.1 (11.4)
Stepping error (mm)	30.41 (38.1)	27.7 (37.5)	25.5 (18.9)	23.3 (11.3)	15.3 (9.5)	14.9 (5.7)	15.7 (9.4)	15.0 (7.4)
Step length (cm)	29.3 (4.8)	18.4 (5.2)	23.7 (8.1)	21.9 (8.3)	28.3 (13.9)	18.8 (9.0)	21.0 (11.1)	22.5 (11.5)

Key- Medio-lateral motion of the centre of pressure (ML-COP), Antero-posterior motion of the centre of pressure (AP-COP), P=paretic leg, NP=Non-paretic leg

ML-COM$_{est}$ peak velocity: ML- COM$_{est}$ peak velocity prior to foot-offset was larger when stepping towards medial compared to lateral targets (Effect of target F (1, 28) =123.4 p<0.001). There was a Target x Group interaction, here the increase in ML- COM$_{est}$ peak velocity when stepping to medial compared to lateral targets was larger for the TD group compared to the CP group (Target x Group interaction F(1,28)=5.4 p<0.05))(Table 4, Figure 2A). There was a Side x Target interaction with the increase in ML- COM$_{est}$ peak velocity when stepping to medial as opposed to lateral targets being larger when stepping with the non-paretic compared to the paretic leg (Figure 2A). There was no group effect (Group F (1, 28) =3.2 p=0.09) or any other interaction effects.

AP-COP peak velocity: The AP-COP moved posterior prior to foot-offset. The data were not normally distributed and groups were compared at each target location using a Mann Whitney test. AP-COP peak was significantly greater when stepping with the non-paretic leg in the TD group (p<0.05) (Table 4).

AP-COM$_{est}$ peak velocity: AP- COM$_{est}$ moved forwards prior to foot-offset. AP- COM$_{est}$ peak velocity was not normally distributed, and groups were compared at each target location using a Mann Whitney test. There were no significant differences between groups (Table 4).

Stepping error and step length: Step length was not significantly different between groups (Table 4). Stepping error was compared at each target location using a Mann Whitney test. Stepping error was significantly higher in children with CP at all target locations (p<0.05, table 4). In the CP group there was a significant relationship between stepping error and the size of the ML-COP peak when stepping with both the paretic or non-paretic legs to either the lateral or medial targets (r=0.55-0.68 p<0.05). Here higher stepping errors were associated with low ML-COP peak values. There was no significant relationship in the TD group (r=0.14-0.47 p>0.05).

Effects of condition severity and impairment profile on ML anticipatory postural adjustment size

The mean ML-COP peak averaged across all targets was higher in children GMFCS 1 (n=7; 46.6 mm +/- 15.1) compared to those GMFCS 2 (n=8; 30.1 +/-22.1) but this was not significantly different (t=-1.7 p>0.05). The participant with GMFCS 3 had a higher level of impairment and balance difficulties. Removal of this participant did not affect the significance of the balance and impairment-based results described above.

The mean ML-COP peak was significantly correlated with the GMFM stand (r=0.71, p<0.002) and walk scores (r=0.72 p<0.002), and the QFM subsections alignment (r=0.66, p<0.006), coordination (r=0.80 p<0.001), stability (r=0.80 p<0.001) and weight shift (r=0.72 p<0.005). In all cases, a lower mean COP peak was associated with a lower score on the QFM. These correlations remained significant after removal of the participant GMFCS III expect for alignment and stability categories.

The mean COP peak was significantly correlated with mean knee extensor strength (r=0.70 p<0.005) and mean hip abductor strength (r=0.75 p<0.001) with lower strength being associated with smaller ML-COP peak (Figure 2B). Mean gastrocnemius passive range was also associated with the mean ML-COP peak (r=0.63 p<0.01) with a lower passive range being associated with smaller ML-COP peak.

In children with CP the AP-COP peak when stepping with the non-paretic leg was associated with the paretic leg gastrocnemius passive range (r=0.77 p<0.01) (Figure 2C). In contrast, there was no significant relationship between the AP-COP peak when stepping with the paretic leg and the non-paretic leg gastrocnemius passive range (r=0.21 p>0.05). All significant correlations remained after removal of the one participant with GMFCS III.

Discussion

This study compared dynamic balance while stepping to medially and laterally placed targets, in children with CP and TD. The objectives were to (a) assess the APAs by measuring the COP, COM estimate (COM_{est}), and stepping accuracy in a group of children with CP and TD (b) investigate the relationship between APA and the type and severity of impairment. The study found that children with CP had reduced APAs when stepping and higher stepping inaccuracy. APA modulation with target position was reduced in children with CP and lower APAs were associated with greater stepping error. APA size correlated with functional ability, measures of impairment and stepping error.

Children with CP showed reduced medio-lateral (ML) APAs; similar to that previously described in children with CP (8) and in adults with hemiplegia post stroke (17, 18). Balance during stepping can be described using the 'throw and catch' model, where the COM is 'thrown' towards the standing leg in a ballistic trajectory towards the target step (7). Findings from this study agree with previous work showing that the preparatory motion prior to swing leg lift off, varies depending on the position of the intended step target (19). Stepping laterally can be thought of as a controlled fall towards the target. APAs when stepping laterally were not markedly different between groups and this reduction in the need to accurately programme APAs may be a reason why children with CP often walk with a wide

base of support. Stepping medially requires a greater ML and AP movement of the COM_{est}. The hip abductors of the leading leg work synergistically with the hip adductors of the stance leg to control the pelvis through this movement (20). In children with CP, greater knee extensor and hip abductor strength was associated with greater ML motion of COP suggesting weakness in these muscles may contribute to smaller ML APAs.

The significant association between the APA size (ML-COP) and the stepping error in children with CP suggests that either poorly scaled APAs directly affect the trajectory of the leg movement and/or that alterations in leg motion are required to maintain balance in the face of an inaccurate APA. However, the error in foot placement was still higher in the CP group when stepping to lateral targets despite a non-significant difference in APA size between groups. This suggests that stepping error may be only partly explained by deficits in APA size and that inaccurate programming of leg movements could also occur.

The AP-COP peak when stepping with the non-paretic leg was associated with reduced range in the contralateral paretic gastrocnemius whilst the opposite relationship (that is, paretic leg AP-COP peak and non-paretic leg gastrocnemius length) was not seen. This suggests a limitation in AP motion of the COM; this could be in part due to reduced range in the contralateral gastrocnemius (9).

This study recruited a small number of participants, thereby limiting the ability to analyse sub-groups. The static standing posture prior to taking a step and the asymmetry in standing posture and load taken by each leg were not measured, which may affect the pattern of dynamic balance (18). Children with CP took shorter steps during the establishment and definition of their individual target step. Although the difference was not significant between the groups, it is a limitation of the study as it may require less dynamic balance to step a shorter distance (19).

Conclusion

Children with CP show smaller ML APAs and this is more marked when they step to more medially placed targets. Medio-lateral APA size may be limited by proximal muscle strength and gastrocnemius length. Limited gastrocnemius range affects AP motion when stepping with the contralateral leg. Targeting such impairments in combination with task related training might help to improve dynamic balance.

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References

1. Pavão SL, dos Santos AN, de Oliveira AB, Rocha NACF. Functionality level and its relation to postural control during sitting-to-stand movement in children with cerebral palsy. Research in developmental disabilities. 2014;35(2):506-11.
2. Hof AL, Gazendam MG, Sinke WE. The condition for dynamic stability. Journal of biomechanics. 2005;38(1):1-8.

3. Massion J. Postural control system. Curr Opin Neurobiol. 1994;4(6):877-87.
4. Winter DA. Human balance and posture control during standing and walking. Gait & posture. 1995;3(4):193-214.
5. Yiou E, Caderby T, Delafontaine A, Fourcade P, Honeine JL. Balance control during gait initiation: State-of-the-art and research perspectives. World J Orthop. 2017;8(11):815-28.
6. Lyon IN, Day BL. Predictive control of body mass trajectory in a two-step sequence. Exp Brain Res. 2005;161(2):193-200.
7. Lyon I, Day B. Control of frontal plane body motion in human stepping. Experimental brain research. 1997;115(2):345-56.
8. Stackhouse C, Shewokis PA, Pierce SR, Smith B, McCarthy J, Tucker C. Gait initiation in children with cerebral palsy. Gait Posture. 2007;26(2):301-8.
9. Feng J, Pierce R, Do KP, Aiona M. Motion of the center of mass in children with spastic hemiplegia: balance, energy transfer, and work performed by the affected leg vs. the unaffected leg. Gait & posture. 2014;39(1):570-6.
10. Hägglund G, Lauge-Pedersen H, Wagner P. Characteristics of children with hip displacement in cerebral palsy. BMC musculoskeletal disorders. 2007;8(1):101.
11. Palisano RJ. GMFCS-E & R Gross Motor Function Classification System: Expanded and Revised: Canchild centre for childhood disability research; 2007.
12. Haugh AB, Pandyan AD, Johnson GR. A systematic review of the Tardieu Scale for the measurement of spasticity. Disability and rehabilitation. 2006;28(15):899-907.
13. Russell DJ, Avery LM, Walter SD, Hanna SE, Bartlett DJ, Rosenbaum PL, et al. Development and validation of item sets to improve efficiency of administration of the 66-item Gross Motor Function Measure in children with cerebral palsy. Developmental medicine and child neurology. 2010;52(2):e48-54.
14. Wright FV, Rosenbaum P, Fehlings D, Mesterman R, Breuer U, Kim M. The Quality Function Measure: reliability and discriminant validity of a new measure of quality of gross motor movement in ambulatory children with cerebral palsy. Developmental Medicine & Child Neurology. 2014;56(8):770-8.
15. O'Connor CM, Thorpe SK, O'Malley MJ, Vaughan CL. Automatic detection of gait events using kinematic data. Gait & posture. 2007;25(3):469-74.
16. Von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. Bulletin of the World Health Organization. 2007;85:867-72.
17. Delafontaine A, Vialleron T, Hussein T, Yiou E, Honeine JL, Colnaghi S. Anticipatory Postural Adjustments During Gait Initiation in Stroke Patients. Frontiers in neurology. 2019;10:352.
18. Brunt D, Vander Linden DW, Behrman AL. The relation between limb loading and control parameters of gait initiation in persons with stroke. Archives of physical medicine and rehabilitation. 1995;76:627-34.
19. Bancroft MJ, Day BL. The Throw-and-Catch Model of Human Gait: Evidence from Coupling of Pre-Step Postural Activity and Step Location. Frontiers in human neuroscience. 2016;10(635).
20. Rogers MW, Pai YC. Organization of preparatory postural responses for the initiation of lateral body motion during goal directed leg movements. Neuroscience letters. 1995;187:99-102.