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RESEARCH ARTICLE

Modulation of gait inter-limb coordination in children with unilateral spastic cerebral palsy after intensive upper extremity intervention

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Abstract

Motor function difficulties associated with unilateral spastic cerebral palsy (USCP) impact gait inter-limb coordination between the upper and lower extremities. Two motor learning based, upper extremity treatments, Constraint Induced Movement Therapy (CIMT) and Hand Arm Bimanual Therapy (HABIT), have resulted in improvements in coordination and function between the arms in children with USCP. However, no study has investigated whether coordination between the upper and lower extremities improves after either intervention during a functional task, such as walking. Gait analysis was performed before and after participation in intensive (3 weeks, 90 h total) CIMT and HABIT interventions to determine if intensive upper extremity treatment can improve inter-limb coordination between the upper and lower extremities of children ($n = 20$, 6–17 years old) with USCP. While upper extremity clinical evaluations indicated hand function improvements, there were no changes in lower extremity parameters for either treatment. However, we found that 10 out of 11 children with a 2:1 arm swing-to-stride ratio at pre-test improved to a 1:1 ratio at post-test. Temporal synchronicity of contralateral limbs, swing displacement of the more affected arm, and arm swing side symmetry unexpectedly decreased. Positive changes in coordination were observed in children who demonstrated poor coordination during walking at pre-test, yet the changes were not robust. Principle component analysis did not indicate changes in limb coupling. While more coordinated, gross-motor training of the upper and lower extremity may reveal greater changes, lower extremity gait patterns were not improved in high functioning children with USCP.

Keywords Cerebral palsy · Children · Gait · Coordination · Intervention

Introduction

Cerebral palsy (CP), the most common childhood physical disability, describes a group of neurodevelopmental disorders attributed to non-progressive disturbances to the developing brain (Bax et al. 2005). Unilateral spastic cerebral palsy (USCP), the most prevalent subtype, is characterized by impaired movement coordination and muscle tone regulation, affecting upper and lower extremity motor function on one side (Bax et al. 2005). These motor difficulties impact functional abilities, including gait (Meyns et al. 2012a, b, 2014; Cappellini et al. 2018). Gait analysis in children with USCP has focused on the lower extremities (Bell et al. 2002; Kim and Son 2014) with little attention paid to upper extremity movement and how upper extremity interventions influence gait (Coker et al. 2010; Zipp and Winning 2012).

During normal walking, arm swing is coupled with the contralateral lower extremity stride (Donker et al. 2001). Temporal synchronicity between contralateral limbs optimizes stability, decreases vertical angular momentum (Park 2008), and minimizes energy consumption (Ortega et al. 2008). This coupling has not been evaluated in children with USCP. The less affected arm of these children typically swings with increased amplitude compared to the more affected arm (Meyns et al. 2011) to counteract heightened angular momentum produced by the legs (Bruijin et al. 2011). The arm swing-to-stride ratio provides a simple approach to looking at coupling. This ratio is 1:1 at preferred and fast walking speeds (greater than 0.80 m/s) and 2:1 at slower velocities for typically developing children (TDC) (Meyns et al. 2012a, b, 2014). In children with USCP, the 2:1 ratio persists for the more affected arm at faster speeds,

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contributing to a less stable gait pattern (Meyns et al. 2012a, b, 2014). While the arm swing-to-stride ratio provides a broad overview of limb coupling, Principle Component Analysis (PCA) provides a more discriminating approach, but has yet to be applied to this population.

To date, all therapies with sufficient evidence to support clinical implementation in USCP involve upper extremity training (Novak et al. 2013). Two motor learning based approaches appear beneficial for improving upper extremity function. Constraint Induced Movement Therapy (CIMT) involves physical restraint of the less affected arm with active training of the more affected arm, while Hand Arm Bimanual Intensive Therapy (HABIT) involves activities using both upper extremities. Both interventions effectively improve coordination and hand function in children with USCP (Gordon et al. 2011), which may impact arm swing and result in gait pattern improvements as efficient gait necessitates effective arm swing. Previous studies suggest improvements in lower extremity gait parameters after CIMT (Coker et al. 2010; Zipp and Winning 2012), yet coordination between the upper and lower extremities after upper extremity intervention is unknown. No studies have examined gait following bimanual training.

Improvements in upper and lower extremity gait interlimb coordination after upper extremity intervention are expected for several reasons. First, if the biomechanics of the upper extremities are changed after an upper extremity intervention, the biomechanics of the lower extremities may consequently change to adhere to the new internal constraints (Donker et al. 2001). This is supported by reports of changes in lower extremity gait patterns when arm swing is manipulated in children with USCP (Delabastita et al. 2016). Second, previous literature shows that upper extremity movement can drive appropriately coordinated, reciprocal movement of the lower extremities with the use of central pattern generators of the spine in both neurologically damaged and intact individuals (Ferris et al. 2006). Finally, two studies have reported improvements in lower extremity gait parameters after participation in CIMT in children with CP (Coker et al. 2010; Zipp and Winning 2012).

The aim of this study was to assess the effect of upper extremity interventions on coupling between upper and lower extremities during walking. It was hypothesized that temporal synchronicity between contralateral limbs (e.g. time difference between peak forward arm swing and contralateral heel strike) would increase and arm swing-to-stride ratio would improve in children with a 2:1 ratio before intervention. Additionally, this study evaluated symmetry between the more affected and less affected upper and lower extremities after upper extremity intervention. It was also hypothesized that lower extremity gait parameters would become closer to TDC values post-intervention. The CIMT group was meant to serve as the control group, specifically since the CIMT intervention used in this study did not require a large amount of gross-motor practice between the upper and lower extremities as some other studies required in their version of CIMT that had indicated improvements in gait. Furthermore, the HABIT group was expected to show greater improvements than the CIMT group since HABIT and efficient, coordinated walking require concurrent movement of the upper extremities.

Methods

Participants

20 children with USCP, 6–17 years old (Table 1), were of a convenience sample recruited for the Teachers College (TC), Columbia University Center for Cerebral Palsy CIMT and HABIT camps as part of an ongoing trial (http://www.clinicaltrials.gov #NCT02918890). Children were recruited from the Center Website (http://www.tc.edu/centers/cit/), online support groups, and NYC clinics. Participants were screened via telephone/email and, if acceptable, invited to receive an on-site physical examination, or one videotaped by their physical/occupational therapist. Inclusion/exclusion criteria were based upon prior CIMT/HABIT trials (Gordon et al. 2005; Charles and Gordon 2006). Inclusion criteria included the ability to extend wrists greater than 20° and metacarpophalangeal joints greater than 10° from full flexion, lift the more affected arm 15 cm above a table and grasp light objects, greater than 50% difference in the Jebsen-Taylor Test of Hand Function (JTTHF) score between hands and a more affected hand time below the maximum,

Table 1 Participant characteristics

	CIMT	HABIT
N	8	12
Age (years)	9.5 (2.4)	10 (3.6)
Male	4	5
Female	4	7
Affected hemisphere—left	3	4
Affected hemisphere—right	4	8
MACS I	1	3
MACS II	3	6
MACS III	4	3
GMFCS I	8	11
GMFCS II	0	1
JTTHF	394.7 (269.4)	342.3 (210.8)

Age and JTTHF are represented as the mean (standard deviation)

MACS Manual Ability Classification System, *GMFCS* Gross Motor Function Classification System, *JTTHF* Jebsen-Taylor Test of Hand Function

follow screening instructions, complete testing, and mainstreamed in school. Exclusion criteria included health problems unassociated with CP, current/untreated seizures, visual problems that would interfere with treatment/testing, severe muscle tone, orthopedic surgery on the more affected upper or lower extremity within the past year, botulinum toxin in the more affected upper or lower extremity within the past six months, and balance problems preventing sling wear. Caregivers provided informed consent. This protocol was approved by the TC, Columbia University Institutional Review Board.

Intervention

Children were randomized into two treatment groups (CIMT or HABIT) using concealed allocation stratified by age and JTTHF score. Interventions occurred in separate rooms where children received 90 h of therapy (6 h/day, 5 days/week for 3 weeks) (see Gordon et al. 2005, 2011; Charles and Gordon 2006 for details). Children worked one-on-one with trained interventionists. Therapy focused on the child's interests, movement deficits, and improvement potential. Walking was never the focus, however, children walked short distances during daily activities including sports and restroom use. Caregivers engaged children in upper extremity activities at home for 1 h daily throughout camp.

CIMT CIMT was adapted to be child-friendly (Gordon et al. 2005). The less affected hand was constrained using a cotton sling strapped to the child's trunk with the end sewn shut, worn continuously during the camp except for restroom use. Children used the more affected arm to perform fine- and gross-motor functional and game activities.

HABIT Children performed fine- and gross-motor bimanual activities chosen based on the more affected arm's role (Charles and Gordon 2006). Complexity progressed from non-dominant passive assist to active manipulator.

Gait analysis

Data were collected pre- and post-intervention. Pre-testing occurred during the 1st or 2nd day of camp and post-testing occurred during the 2nd-to-last or last day. Children walked across an 8-m walkway 10 times at a self-selected speed. Trials were recorded using an 8-camera 3D motion capture system (Vicon Workstation 612, Lake Forest, CA) with a Plug-In-Gait marker application. Gait parameters during the middle 4-m of the walkway were analyzed to discount acceleration and deceleration. The first three trials of unimpeded gait with visible markers were analyzed, based on previous gait studies involving this population (Meyns et al. 2011; Bohm and Doderlein 2012). Data were sampled at 120 Hz and filtered using a low-pass Butterworth filter with a cutoff frequency of 6 Hz. Analysis utilized custom LabView 8.6 software (National Instruments, Austin, TX).

The primary outcome measures included temporal synchronicity of contralateral limbs and arm swing-to-stride ratio. Secondary outcome measures included individual arm swing displacement and velocity (Meyns et al. 2011), arm temporal synchronicity, stance time, swing time, step length, single limb support percentage, cadence, walking velocity, and limb coupling using PCA (e.g., percent variance explained by the first principal component). Secondary outcome measures also included side and absolute symmetry ratio (Hsu et al. 2003; Bohm and Doderlein 2012) for step length, swing time, stance time, and arm swing displacement. Side symmetry ratios divided values of the more affected side by the less affected side and absolute symmetry ratios divided smaller by larger values, regardless of side. Symmetry ratios were determined to be outside of TDC values if larger than 10% (Wheelwright et al. 1993). Clinical hand evaluations included the JTTHF, Box and Blocks test, Assisting Hand Assessment (AHA), and the ABILHAND-Kids. See Table 2 for details.

Statistical analysis

Data were analyzed using SPSS version 24 (SPSS, Chicago, Illinois). Initially we conducted 2(group) × 2(test session) ANOVAs with repeated measures on test session. However, Kolmogorov–Smirnov tests determined data were not normally distributed for many measures. A log base 10 transformation left many variables still non-normally distributed. Therefore, Wilcoxon Signed-Rank tests were conducted between pre- and post-intervention (median) data for all dependent variables, except for the arm swing-to-stride ratio where a McNemar's test was used. While results were qualitatively similar regardless of statistical procedure (parametric or non-parametric), we only report non-parametric tests. Median Absolute Deviation (MAD), a robust measure of central tendency immune to sample size (Leys et al. 2013), evaluated data dispersion. Mann–Whitney *U* tests were used to determine group differences. Significance was set at $p < 0.05$.

Results

Table 1 shows participant characteristics. Age and clinical evaluation scores between children in the CIMT and HABIT groups were comparable. There were no differences in the response to treatment between groups for any measure ($p > 0.05$ for all cases). Consequently, groups were collapsed for subsequent analyses. Upper extremity clinical evaluations including the AHA, Box and Blocks test for both hands, and ABILHAND-Kids significantly improved

Table 2 Descriptions of primary and secondary variables

Variable	Description
Temporal synchronicity of contralateral limbs	Time between peak forward arm swing and contralateral heel strike
Arm swing-to-stride ratio	Number of arm swings per stride on the same side of the body
PCA limb coupling	Represents patterns of similarity
Side symmetry ratio	Values of the more affected side divided by the less affected side
Absolute symmetry ratio	Smaller values divided by larger values regardless of side
Arm swing displacement	Difference of displacement between the maximum and minimum respective sagittal plane arm markers
Arm swing velocity	Difference in velocity between the maximum and minimum respective sagittal plane arm markers
Arm temporal synchronicity	Time between peak forward arm swing of one arm and peak backward swing of the other
Stance time	Time from heel strike to toe-off of the same limb
Swing time	Time from toe-off to heel strike of same limb
Step length	Distance between toe-off and heel strike of same limb
Single limb support	Percentage of time spent of one limb during the gait cycle
Cadence	Number of steps per minute
Walking velocity	Self-selected walking velocity
Jebsen–Taylor test of hand function	A measure of hand function during simulated activities of daily living
Box and blocks	A measure of unilateral gross manual dexterity
Assisting hand assessment	A measure of how children with unilateral upper limb disability use the more affected hand with the less affected hand in bimanual play
ABILHAND-kids	A measure of manual ability for children with upper limb impairment

Italicized variables represent primary outcome measures

post-treatment, while the JTTHF did not (Table 3). Two of the primary outcome variables, temporal synchronicity between contralateral limbs and arm swing-to-stride ratio, indicated changes after treatment, with the decrease in synchronicity reaching significance (Table 4). No changes in secondary lower extremity gait parameters or lower extremity symmetry were evident at post-test (Table 4) ($p > 0.05$ for all cases). While there was a decrease in swing time MAD ($p = 0.021$) and cadence MAD ($p = 0.017$) of the less affected leg, no change in MAD for any other gait parameter was observed (Table 4). PCA did not indicate changes in limb coupling (Table 5).

Figure 1a, b shows kinematic traces of contralateral upper and lower limb trajectories of a representative child (e.g., the data of this child reflects changes observed in the entire treatment group, see Table 4) during one walking trial pre- and post-intervention (HABIT). An increase in time (vertical lines) between heel strike (HS) and maximum forward arm swing (AS) represents a decrease in temporal synchronicity between contralateral limbs at post-test (Fig. 1a, b). Additionally, smaller peaks of the more affected arm in both directions at post-test indicate shorter swing displacement compared to pre-test (Fig. 1b). As described below, these findings were representative of the group.

Table 3 Clinical evaluations of hand function

		Pre-test	Post-test	*Z*	*p* value
Both sides included	AHA	53.50 (15.75)	57.00 (14.75)	− 3.21	**0.001**
	ABILHAND-Kids	1.78 (1.22)	2.94 (1.49)	− 3.06	**0.002**
More affected side	JTTHF	374.41 (351.33)	231.63 (325.98)	− 1.87	0.06
	BB	13.00 (12.75)	15.00 (11.75)	− 2.63	**0.01**
Less affected side	JTTHF	50.63 (13.92)	50.00 (20.85)	− 0.04	0.97
	BB	38.50 (18.25)	42.00 (11.00)	− 2.28	**0.02**

Data are presented as median (interquartile range)

AHA Assisting Hand Assessment, *JTTHF* Jebsen–Taylor Test of Hand Function, *BB* box and blocks

Bold *p* values indicate significance ($p < 0.05$)

Table 4 Comparison of primary and secondary variables and associated MAD at pre- and post-test using the Wilcoxon test

	Variable	Pre-test	Post-test	*Z*	*p* value
Both sides included	Arm swing side symmetry ratio	0.89 (0.74)	0.66 (0.34)	− 2.99	**0.003**
	MAD	0.12 (0.25)	0.07 (0.09)	− 2.73	**0.006**
	Arm swing absolute symmetry ratio	0.71 (0.32)	0.59 (0.31)	− 1.15	0.25
	MAD	0.05 (0.06)	0.05 (0.06)	− 1.26	0.20
	Step length side symmetry ratio	0.99 (0.03)	1.00 (0.03)	− 1.19	0.23
	MAD	0.01 (0.03)	0.02 (0.02)	− 0.15	0.88
	Step length absolute symmetry ratio	0.98 (0.03)	0.99 (0.03)	− 0.78	0.43
	MAD	0.00 (0.02)	0.02 (0.02)	− 0.44	0.65
	Swing time side symmetry ratio	0.97 (0.10)	1.01 (0.13)	− 0.72	0.46
	MAD	0.04 (0.05)	0.03 (0.05)	− 1.08	0.28
	Swing time absolute symmetry ratio	0.94 (0.08)	0.96 (0.10)	− 0.80	0.94
	MAD	0.01 (0.03)	0.01 (0.02)	− 0.37	0.97
	Stance time side symmetry ratio	1.01 (0.16)	0.98 (0.21)	− 0.48	0.63
	MAD	0.04 (0.05)	0.03 (0.04)	− 0.45	0.65
	Stance time absolute symmetry ratio	0.92 (0.08)	0.93 (0.09)	− 0.04	0.97
	MAD	0.03 (0.03)	0.02 (0.03)	− 0.82	0.41
	Walking velocity (m/s)	1.18 (0.28)	1.12 (0.22)	− 1.30	0.19
	MAD	0.03 (0.07)	0.04 (0.06)	− 0.64	0.53
More affected side	*Temporal synchronicity of contralateral limbs (s)*	0.13 (0.32)	0.40 (0.21)	− 2.80	**0.005**
	MAD	0.05 (0.07)	0.06 (0.09)	− 0.88	0.38
	Arm swing frequency (Hz)	2.88 (1.35)	2.70 (2.43)	− 0.59	0.55
	MAD	0.52 (0.71)	0.48 (0.50)	− 0.82	0.41
	Arm swing displacement (m)	0.25 (0.13)	0.17 (0.10)	− 3.24	**0.001**
	MAD	19.24 (37.76)	13.9 (14.68)	− 0.93	0.35
	Velocity of total arm swing (m/s)	0.59 (1.19)	0.44 (0.38)	− 2.12	**0.03**
	MAD	0.13 (0.18)	0.07 (0.12)	− 1.23	0.22
	Temporal synchronicity of arms (s)	0.12 (0.10)	0.10 (0.08)	− 1.06	0.28
	MAD	0.03 (0.05)	0.03 (0.03)	− 0.35	0.72
	Step length (m)	1.14 (0.21)	1.10 (0.14)	− 0.18	0.85
	MAD	16.02 (23.1)	18.76 (30.75)	− 0.37	0.71
	Swing time (s)	0.54 (0.07)	0.54 (0.09)	− 0.07	0.94
	MAD	0.01 (0.03)	0.01 (0.00)	− 1.72	0.09
	Stance time (s)	0.40 (0.18)	0.45 (0.16)	− 0.56	0.57
	MAD	0.02 (0.03)	0.10 (0.06)	− 2.32	**0.02**
	Cadence (steps/min)	122.57 (27.15)	120.48 (22.73)	− 0.74	0.45
	MAD	3.75 (5.01)	3.38 (6.24)	− 1.01	0.31
	Single limb support (%)	43.29 (6.42)	45.07 (7.57)	− 0.48	0.63
	MAD	0.38 (2.05)	0.35 (0.88)	− 0.72	0.47

Table 4 (continued)

	Variable	Pre-test	Post-test	*Z*	*p* value
Less affected side	*Temporal synchronicity of contralateral limbs (s)*	0.15 (0.14)	0.29 (0.18)	− 2.44	**0.01**
	MAD	0.04 (0.05)	0.03 (0.04)	− 0.60	0.55
	Arm swing frequency (Hz)	2.13 (0.52)	2.04 (0.37)	− 0.18	0.85
	MAD	0.13 (0.40)	0.08 (0.13)	− 1.46	0.15
	Arm swing displacement (m)	0.27 (0.14)	0.27 (0.16)	− 0.97	0.33
	MAD	21.60 (40.96)	32.6 (37.31)	− 0.37	0.71
	Velocity of total arm swing (m/s)	0.55 (0.27)	0.56 (0.34)	− 0.61	0.53
	MAD	0.07 (0.08)	0.06 (0.10)	− 0.89	0.37
	Temporal synchronicity of arms (s)	0.10 (0.11)	0.14 (0.010)	− 1.56	0.11
	MAD	0.04 (0.04)	0.04 (0.03)	− 0.15	0.88
	Step length (m)	1.13 (0.15)	1.08 (0.18)	− 1.64	0.10
	MAD	21.6 (23.53)	22.9 (39.86)	− 0.67	0.50
	Swing time (s)	0.56 (0.11)	0.52 (0.13)	− 0.95	0.34
	MAD	0.02 (0.03)	0.01 (0.02)	− 1.09	0.28
	Stance time (s)	0.44 (0.09)	0.46 (0.15)	− 0.35	0.72
	MAD	0.01 (0.03)	0.02 (0.02)	− 0.33	0.74
	Cadence (steps/min)	124.15 (20.88)	120.63 (25.77)	− 0.75	0.94
	MAD	3.75 (7.06)	1.28 (3.31)	− 2.89	**0.02**
	Single limb support (%)	44.96 (5.47)	44.71 (6.02)	− 0.45	0.65
	MAD	0.68 (1.29)	0.47 (1.29)	− 0.12	0.91

Data are presented as median (interquartile range). MAD values are listed below the associated variable. Italics represent primary variables
Bold *p* values represent significance ($p < 0.05$)

Table 5 Principle component analysis

	UE and LE		UE only	
	Pre-test	Post-test	Pre-test	Post-test
% variance PC1	49.84 (12.63)	51.61 (10.39)	52.89 (9.36)	56.42 (17.18)
Z score	− 0.62		− 0.97	
p value	0.53		0.33	

Data are presented as median (interquartile range)

Intensive upper extremity intervention improves upper and lower extremity inter-limb coordination in children with poor coordination before intervention

Children demonstrated a decrease in synchronicity between contralateral limbs associated with both the more ($p = 0.005$) and less affected ($p = 0.014$) arms (Fig. 2; Table 4), though no associated change in MAD was observed (Table 4). These decreases were not associated with any change in walking velocity (Fig. 2). Arm swing-to-stride ratio of the sample did not change significantly for either arm (Table 4); however, only 11 children displayed a pre-test 2:1 ratio on either the more (5) or less affected (6) side. Ten out of the 11 children who indicated a 2:1 ratio at pre-test improved to a 1:1 ratio after the intervention (shown by McNemar's test) ($p = 0.002$). All five children with a 2:1 ratio of the less affected arm changed to 1:1 post-intervention ($p = 0.025$). Five children changed from 2:1 to 1:1 on the more affected side, while one child remained at the 2:1 ratio ($p = 0.025$). All other children (15 on the less affected side and 14 on the more affected side) retained the 1:1 ratio at which they started. Furthermore, these improvements were not related to walking velocity. Follow-up t-tests indicated that there was no change in velocity from pre- to post-test in the subset of children who improved their arm swing-to-stride ratio for either the more ($t(5) = -1.30$, $p = 0.12$) or less affected ($t(5) = 1.02$, $p = 0.18$) sides. While the decrease in contralateral limbs synchronicity was unexpected, the move towards a 1:1 ratio for all but one child suggests that inter-limb coordination was improved in children that showed poor coupling at pre-test.

Changes in arm swing during walking

According to the side symmetry ratio, the arms became less symmetric at post-test ($p = 0.003$); however, the absolute symmetry ratio did not change significantly. The side symmetry decline may be attributed to the decrease in arm swing displacement of the more affected arm from 0.25 to 0.17 m ($p = 0.001$) and velocity from 0.59 to 0.44 m/s ($p = 0.033$), while the less affected arm did not change. No changes in MAD of side or absolute symmetry of upper or lower extremities were noted (Table 4). Neither temporal synchronicity between the arms nor associated MAD changed (Table 4).

Discussion

The aim of this study was to determine if CIMT or HABIT improve coordination between the upper and lower extremities during walking. No differences between groups were evident. The hypothesis that contralateral limb synchronicity, a primary variable, would improve was not supported. However, the hypothesis that arm swing-to-stride ratio, another primary variable, would improve was partially supported, as all but one child with a pre-test 2:1 ratio improved to a 1:1 ratio at post-test. Lack of significance associated with arm swing-to-stride ratio may be due to a ceiling effect, as the majority of children already had a 1:1 ratio at pre-test. The hypothesis that the upper and lower extremities would become more symmetrical was not supported. Though a decrease in arm swing displacement of the more affected arm and side symmetry between arms was observed at post-test, overall limb coupling during gait improved. This is evidenced by the arm swing-to-stride ratio, which is the most important measure since it is well known and previously implemented in this population compared to temporal synchronicity that has never been used in children with USCP prior to this study. Therefore, despite the improvement in upper extremity clinical measures, the carry over to gait coordination was modest.

Kinematics may reveal compensatory strategies

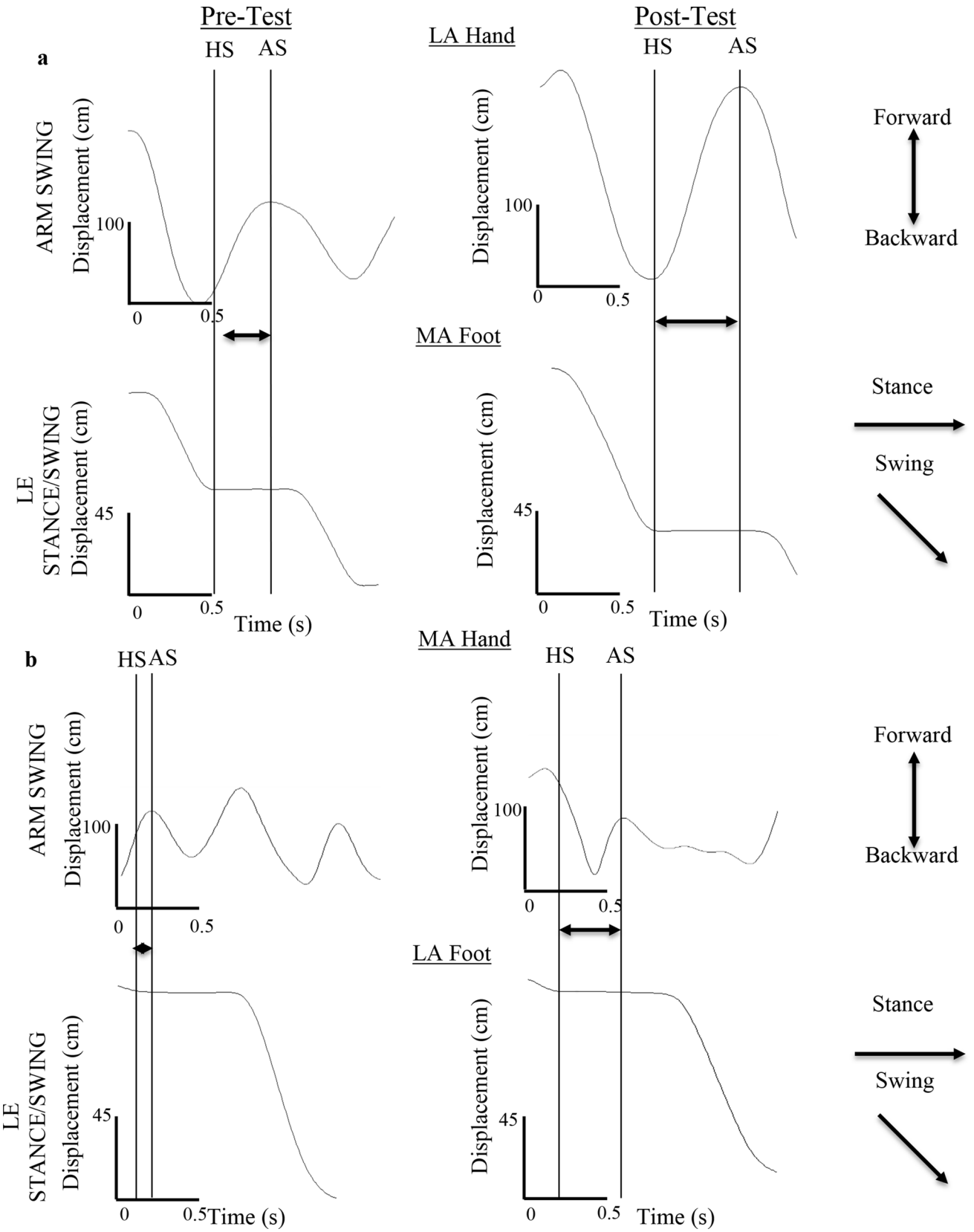
As this is the first study to analyze kinematics of upper and lower extremity inter-limb coordination after CIMT/HABIT, it may have highlighted upper extremity impairment compensation strategies such as the decreases in more affected arm swing and temporal synchronicity of contralateral limbs. 35% of children (7 out of 20) demonstrated a larger arm swing of the more affected arm than the less affected arm at pre-test; however, this percentage decreased to 10% (2 out of 20) at post-test. Though absolute symmetry did not significantly improve, 7 out of 20 children became more symmetric (3 out of 7 of whom demonstrated a larger arm swing of the more affected arm at pre-test). Importantly, side and absolute symmetry ratios indicated post-test changes in the same children, but the magnitude was much larger for side than absolute symmetry. Furthermore, these changes in arm swing were not related to velocity, as there were no significant increases in velocity in either treatment group at post-test.

Sample and intervention differences may elicit discrepancies with previous literature

While many studies have established improvements in upper extremity function after CIMT and HABIT (Gordon et al. 2005, 2011; Charles and Gordon 2006), only two have evaluated the lower extremities following CIMT (Coker et al. 2010; Zipp and Winning 2012). This is the first study to evaluate the effect of HABIT on the lower extremities and gait inter-limb coordination after either intervention. The expectation that changes in the HABIT group would be greater than the CIMT group was not met, therefore the upper extremity intervention type implemented (bimanual or constraint) may not have consequences on gait patterns of children with USCP.

This study's results contrast those of Zipp and Winning (2012). While children in both studies were within two standard deviations (2SD) of TDC values pre- and post-intervention, Zipp and Winning (2012) reported increased velocity at post-test. Interestingly, children in the present study walked faster (1.18 m/s) than those in the Zipp and Winning (2012) study (1.04 m/s) at pre-test, but had similar velocities at post-test. Cadence showed the same relationship. McNemar's test was also used to determine if children in this study with values outside of 2SD of age-matched TDC improved to be within 2SD at post-test (Lythgo et al. 2011; Menkveld et al. 1988). However, neither gait parameter associated with children in this study improved to be within 2SD at post-test.

Although Coker et al. (2010) reported no significant improvement in lower extremity symmetry after CIMT, they reported that 50% of children decreased step time difference between legs. This study's group was already within 10% asymmetry associated with TDC (Menkveld et al. 1988) at pre-test. However, our data show between 2 and 5 children had greater than 10% asymmetry per lower extremity variable at pre-test and 2–3 of those children improved to be less than 10% per variable at post-test. Though normalized step length was outside 2SD of TDC for both studies, this sample's normalized velocity was within 2SD pre- and post-intervention, while Coker et al. sample (2010) was outside 2SD at pre-test and improved to be within 2SD at post-test. Coker et al. (2010) also reported children starting the intervention with a lower cadence and ending with a higher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HS
AS
Displacement (cm)
100
0
0.5
MA Foot
Displacement (cm)
45
0
0.5
Time (s)
Forward
Backward
Stance
Swing
b
HS
AS
ARM SWING
Displacement (cm)
100
0
0.5
LE
STANCE/SWING
Displacement (cm)
45
0
0.5
Time (s)
MA Hand
HS
AS
Displacement (cm)
100
0
0.5
LA Foot
Displacement (cm)
45
0
0.5
Time (s)
Forward
Backward
Stance
Swing

◂**Fig. 1** **a** Kinematic traces of the less affected arm and more affected foot displacements in the anterior–posterior direction for one gait cycle of a representative HABIT participant (Participant 1) at pre- and post-test. **b** Kinematic traces of displacements of the more affected arm and less affected foot from the same participant for one gait cycle at pre- and post-test. *MA* more affected, *LA* less affected, *HS* heel strike; *AS* peak forward arm swing

cadence compared to children in this study. Furthermore, children in Coker et al. (2010) study demonstrated single leg support values of the more affected leg outside 2SD of TDC at both pre- and post-test, while this study's children were within 2SD at both sessions. However, it is important to use caution when comparing the data reported in this study to normative TDC data, as these comparisons are made to TDC datasets published in previous literature. Therefore, a direct comparison cannot be made since a TDC group was not collected in this study.

Lack of significant improvement in the lower extremity variables in this study is likely due to pre-test patterns similar to TDC, though individual improvements were evident. This is supported by the greater number of children in GMFCS level I than level II in this study (1 out of 20 in GMFCS II) compared to studies of both Zipp and Winning (2012) (8 out of 16 in GMFCS II) and Coker et al. (2010) (4 out of 12 in GMFCS II, 1 out of 12 in GMFCS III). Additionally, Coker et al. (2010) included children with a mean age much younger (4.3 years) than children in this study (9.8 years), which may have allowed for greater improvements based on the immaturity, and therefore greater potential plasticity, of their gait patterns (Sutherland et al. 1980). Discrepancies may also be due to Coker et al.'s (2010) modified version of CIMT, which incorporated more gross-motor tasks compared to this study (~ 13% total intervention time). However, small sample size may have underpowered our study.

While PCA did not indicate improvements, arm swing-to-stride ratio showed increased coupling in 10 out of 11 children. Discrepancies in these outcomes may be due to computational differences. PCA represents patterns of similarity by expressing data as a set of new orthogonal variables after extracting the most important information (Abdi and Williams 2010). In contrast, the arm swing-to-stride ratio represents coordinative patterns resulting from frequency locking between upper and lower extremities (Donker et al. 2001). Therefore, the arm swing-to-stride ratio provides a broad view while PCA provides a more detailed limb coupling evaluation. While previous literature utilized the arm swing-to-stride ratio to determine gait coordination in children with USCP (Meyns et al. 2011), PCA has never been used in a similar way. Instead, PCA was applied to determine segmental and angle covariation in this population (Bleyenheuft and Detrembleur 2012; Bleyenheuft et al. 2013). Though all requirements to perform PCA with this data set were met, the use of PCA in this study may be inappropriate for this subpopulation with gait characteristics so similar to TDC.

Limitations

Limitations included the unequal number of group participants, small sample size, and lack of a no-treatment control group, though the CIMT group was meant to serve as a control for the HABIT group. Absence of a group of TDC to which we could directly compare our data is also a limitation of this study. Additionally, this convenience sample was high functioning and therefore it is unknown how coordinative changes would differ in more affected children. A ceiling effect may be noted since walking is not a novel task and these children were already walking proficiently. Future research should include children with USCP with a specified coordination deficit of a 2:1 arm swing-to-stride ratio to make stronger conclusions about the potential improvements of limb coupling during walking after either HABIT or CIMT. Inclusion of more gross-motor activities focused on coordination between the upper and lower extremities should also be in future research studies focusing on inter-limb coordination in this population.

Rehabilitation implications

Children with clear deficits in gait coordination, such as a 2:1 arm swing-to-stride ratio, can benefit from an intensive upper extremity intervention in both upper extremity function and coordination between the upper and lower extremities during walking. Therefore, rehabilitation for those children should include either increased time spent performing continuous motor tasks or gross-motor tasks. If possible, continuous gross-motor tasks, such as marching, dancing, or sport should also be included. Practice of such tasks may advance their inter-limb coordination skills further than an intervention focused solely on discrete tasks and result in an improvement in other, more discriminating measures of coordination and limb coupling, such as PCA.

Conclusions

CIMT and HABIT can induce changes in gait inter-limb coordination between upper and lower extremities. Specifically, children with a 2:1 arm swing-to-stride ratio can adapt a 1:1 ratio after participation in an intensive upper extremity intervention. One might ask whether task specificity is of major importance when evaluating lower extremity gait patterns after an upper extremity intervention, but it should be noted that previous literature has

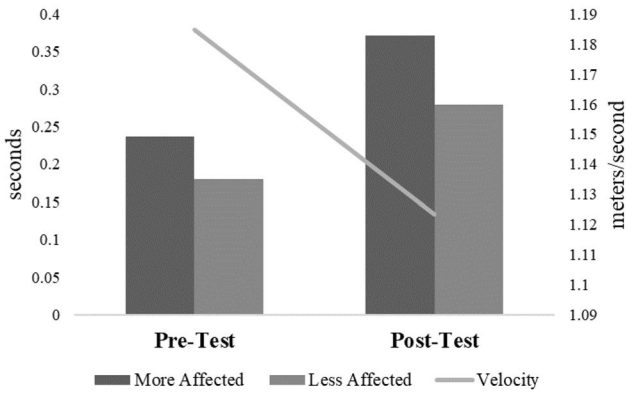

Fig. 2 Relationship between velocity (line) and contralateral limb synchronicity (bars) of the more affected (dark gray) and less affected (light gray) side

reported improvements in clinical gait measures, such as the 6-min walk test, after participation in HABIT-Including the Lower Extremity (HABIT-ILE) (Bleyenheuft et al. 2017). However, while clinical measures of gait improved after HABIT-ILE, the biomechanical modifications of gait patterns are unknown. A greater focus on training of the upper and lower extremities, may have elicited greater improvements in this study (Bleyenheuft et al. 2017).

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

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