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Influence of accuracy constraints on bimanual coordination and gait performance in children with unilateral spastic cerebral palsy

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ABSTRACT

Background: Children with unilateral spastic cerebral palsy (USCP) have both upper and lower extremities movement impairments of their more affected side. Many daily activities require whole body movement control. However, most studies for children with USCP only evaluated either upper or lower extremity impairments.
Research Question: The present study aimed to assess the effects of accuracy constraints on walking and bimanual coordination for children with USCP during a whole body task.
Methods: Ten children with USCP (age: 7–12 years; GMFCS levels: I - II) and ten age-matched typically-developed children (TDC) participated in the study. They were asked to walk and carry a water bottle with and without a cap using a tray at a preferred speed while 3-D kinematic analyses were performed. The two tasks of carrying a water bottle with and without a cap were each performed 5 trials with randomized order between participants.
Results: TDC significantly decreased their walking speed, stride length, height differences between the two hands (symmetric bimanual coordination), vertical hand movement, and elbow joint excursion under higher accuracy constraints with no water bottle cap. Children with USCP showed significantly decreased walking speed, vertical hand movement, and elbow joint excursion under higher accuracy constraints. Children with USCP also significantly decreased walking deviation of line of progression.
Significance: It is exciting to see that children with USCP GMFCS levels I and II were able to maintain their bimanual coordination and modify their gait performance under higher accuracy constraints. Therefore, future treatments or assessments could consider manipulating accuracy constraints even during complex whole body tasks for children with USCP.

1. Introduction

Children with unilateral spastic cerebral palsy (USCP) have early non-progressive lesions of their brains that lead to several motor impairments on their more affected side, including both upper and lower extremities [e.g., 1,2]. Their more affected upper extremities have been shown to move slowly with poor prehension control deficits [e.g., 3–7]. Children with USCP were found to be able to coordinate both hands during simple symmetric bimanual reaching and grasping tasks by slowing down the less affected side to compensate for the more affected side [8]. They showed poor bimanual coordination, especially during asymmetric bimanual coordination task, higher accuracy demanding task or higher complexity task, because the less affected side failed to compensate for the more affected side [9–15]. However, these upper extremity tasks for children with USCP were performed during simple sitting condition.

Most children with USCP are able to walk independently with some gait impairments such as reduced step length, slower speed, impaired gait stability, and wider step width [e.g., 16–18]. However, most of the gait analyses for children with USCP were performed during simple over ground walking. One important daily function of walking is carrying objects to different locations. During our daily functional activities, we carry various objects under different conditions, such as carrying a cup of coffee on the street. Such functional high complexity dual task (walking while carrying objects) activity should be even more challenging for children with USCP. Hung & Meredith evaluated the effects of dual task constraints on gait and bimanual performance using a box carrying task in children with USCP [19]. Children with USCP were found to show more impaired gait performance under dual task constraints (box carrying) than simple walking when compared to typically-developed children (TDC). Children with USCP also displayed less symmetric bimanual coordination when compared to TDC under dual task constraints [19]. This indicated that dual task constraints of box carrying and walking interfered with the compensating ability of

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the less affected side.

Besides simple box carrying, carrying various objects using a tray is a common school activity at lunch time and can also be part of training protocols for children with mild USCP during therapy. It is a common protocol to challenge children with mild USCP to carry various objects, such as a heavily weighted object or a cup of water for precise movement control. However, influences of these additional task constraints during functional whole body tasks are not clear. When carrying objects that may spill or break, the task will need to be performed with precise steadiness (high accuracy constraints). Such higher accuracy constraints while performing dual tasks of carrying objects may interfere with gait performance and compensatory strategies of the less affected hands for bimanual coordination in children with USCP.

Most previous studies concentrated on only upper or lower extremity impairments separately, the understanding of factors that influence dual task performance involving both upper and lower extremities for children with USCP is limited. The influence of such higher accuracy constraint on dual task performance (carrying objects) is unknown for children with USCP. Therefore, in this study, we investigated the influence of accuracy constraints on gait and bimanual coordination during a functional dual task for children with and without mild USCP. We hypothesized that higher accuracy constraints will decrease gait performance and bimanual coordination for children with USCP, but not TDC. Specifically, children with USCP will 1) decrease walking speed, 2) decrease stride length, 3) decrease minimum toe clearance, 4) increase bilateral vertical position differences of their hands, 5) increase vertical hand ROM and 6) increase lateral hand ROM due to increased accuracy constraints.

2. Methods

2.1. Participants

Thirteen children with USCP were recruited between 2015 and 2016; however, three of them were unable to perform the task successfully (could not hold the tray at the starting position). Thus, a total of ten children with mild USCP (age 7–12 years, MACS levels: I—II; GMFCS levels: I—II) and ten age-matched TDC participated in the current study. Their basic descriptive information is shown in Table 1. Hand dominance was determined by their writing hand. Leg dominance was defined by their kicking leg. The age range, MACS, and GMFCS levels were selected because the complexity of the tasks and the extensive nature of the testing session for children with USCP. Children who were able to follow instructions, were not significantly cognitively impaired, and were able to walk and carry a tray independently were chosen to participate in this study. Children were excluded from this study if they had: 1) visual problems that would prevent them from carrying out the testing tasks, 2) any health problems which were not associated with CP, and 3) seizures. Children with USCP were recruited through our previous participants, and online CP support group. Informed consent was obtained from all participants and their caregivers, and the study was approved by the University Institutional Review Board.

Table 1
Baseline Participant Characteristics.

Characteristics	Unilateral CP (n = 10)	TDC (n = 10)
Mean Age (*SD*) y,m	9,7 (2,2)	9,4 (1,8)
Average Height (*SD*) m	1.38 (0.16)	1.38 (0.15)
Average Mass (*SD*) kg	31.6 (13.3)	30.2 (9.3)
Gender		
Male	6	6
Female	4	4
Dominant Hand		
Right	4	10
Left	6	
Lesion Location (type)		
Right	4 (1^a;2^b;1^c)	
Left	6 (0^a;5^b;1^c)	
MACS		
I	2	
II	8	
GMFCS		
I	3	
II	7	

Abbreviations: SD = Standard deviation; TDC = Typically-developed children; MACS = Manual Ability Classification System for individuals with CP. GMFCS = Gross Motor Function Classification System. [a] Brain malformation; [b]Abnormalities of periventricular white matter; [c] Cortical/subcortical lesions. * = $p < 0.05$ Unilateral CP group compared with TDC.

2.2. Procedure and experimental setup

Children were asked to walk along a flat 4 m long path under two conditions at a self-selected pace: walking while carrying a water bottle with a cap (low accuracy constraint condition) and without a cap (high accuracy constraint condition) using a tray with both hands. The tray (34 x 24 cm) had adjustable handles (width range: 34–54 cm) to match the shoulder width of the child and the weight was 620 g with the water bottle filled up. The amount of water was checked and maintained after each trial. The order of the two conditions was randomized between subjects. During both conditions, children were instructed to carry the tray leveled without touching their body while their elbows kept at about ninety degree flexion. To familiarize with the tasks, participants had two practice trials prior to the five collected trials. If a trial was not performed correctly (e.g., the tray touched the body), the child was asked to perform the trial again. Four trials were removed during data collection of all 10 participants (2 trials: dropped the tray; 2 trials: held the tray against their body). Each trial began with an auditory go signal and ended when the child reached an end line taped on the floor. 10 trials were collected from each participant.

Three-dimensional kinematic data were collected during each trial. Whole body plug-in-gait model with 8 infrared cameras of VICON Nexus 1.51 was used. Reflective markers were placed based on plug-in-gait model: bilaterally on the anterior and posterior portions of the head, the shoulders (acromion process), the elbows (lateral epicondyle), the wrists (radio and ulnar styloid processes), the hands (index MCP joint), the upper arms, the forearms, the anterior and posterior superior iliac spines, the lateral thighs, the knee joints (lateral epicondyle), the tibias, the ankle joints (lateral malleolus), the heels and the toes (second metatarsal head). Markers were also placed between the clavicles, on the sternum, on the right scapula, on the spinous process of cervical 7, and on the spinous process of thoracic 10. All markers were digitized at a rate of 120 Hz and were processed with a low pass digital filter with a cutoff frequency of 6 Hz.

2.3. Data analyses

There were about 4 gait cycles during each trial. Two middle gait cycles were selected from each trial for kinematic analysis. The first and the last gait cycle were excluded from further analysis to avoid possible influences of gait initiation and slowing down in the beginning and the end of the walking path. Thus, a total of 10 gait cycles (2 gait cycles x 5 trials) was used for data analysis for each condition. Average values among the 10 gait cycles of all the variables from each participant were used for statistical analysis. Our primary measures were walking speed, stride length, minimum toe clearance [20], vertical positon differences of the hands (to assess whether the tray was carried with its top leveled), vertical range of motion (ROM) of the tray, and lateral ROM of the tray. More affected/non-dominant hand marker ROM during one

gait cycle was used to assess the steadiness of the tray [19]. If the tray was carried unleveled (tilted), the vertical position (height) of both hands would be very different. If the tray moved up and down a lot during a gait cycle, the vertical ROM of the hand marker would be large. Our secondary measures included step width, line of progression during walking (lateral deviation of pelvis progression during a gait cycle: lateral deviation of less-affected/dominant side posterior superior iliac spine marker), elbow joint excursion, and shoulder joint excursion. Elbow and shoulder relative joint angles in the sagittal plane were measured first and then the joint excursions were calculated (maximum joint angle - minimum joint angle) during each gait cycle [19]. There were no significant differences in bodyweight (measured by mass, $p = 0.79$) and height ($p = 0.97$) between the two groups.

Repeated measures ANOVAs (linear model) with one between factor (2 groups), and two within factors of tasks (water bottle with and without a cap) and sides (more affected/non-dominant v.s. less affected/dominant) were performed on all parameters collected from both sides separately. For measures with no separate data from each side, repeated measures ANOVAs with one between factor (2 groups) and one within factors of tasks (water bottle with and without a cap) were performed. Assumptions of homogeneity of variance and sphericity were met for all variables based on Levene's test. Post-hoc comparisons were carried out using the Tukey procedure. Statistical significance was set at $p < 0.05$.

3. Results

Children with USCP had slower walking speed than the TDC under both low and high accuracy constraint conditions (Table 2, group: $F_{1,18} = 18.03$, $p < 0.001$). Both groups decreased their speed under higher accuracy constraint condition (carrying water bottle without a cap, task: $F_{1,18} = 45.51$, $p < 0.001$). Both TDC and children with USCP groups decreased their speed by about 17%. There was a significant group and task interaction for stride length measurements (group x task: $F_{1,18} = 5.42$, $p = 0.03$). Based on post-hoc analyses, TDC significantly decreased their stride lengths (11%) under higher accuracy constraint conditions while children with USCP had no significant change (4%). Therefore, children with USCP had significantly shorter stride lengths than TDC under low accuracy conditions but not under high accuracy conditions. For minimum toe clearance, there were significant interactions between group and the side of the body (Table 2, group x side: $F_{1,18} = 6.15$, $p = 0.023$). Based on post-hoc analyses, children with USCP had lower toe clearance of the more affected side than the less affected side, while TDC had no difference between the two sides. There were no significant findings for step width (Table 2, group: $F_{1,18} = 1.34$, $p = 0.26$; task: $F_{1,18} = 0.25$, $p = 0.62$; group x task: $F_{1,18} = 2.77$, $p = 0.11$). For line of progression during walking, there was significant group and task interaction (group x task: $F_{1,18} = 56.64$, $p < 0.001$). Post-hoc analyses indicated that children with USCP had greater walking deviation than TDC under the no cap condition and decreased their walking deviation under high accuracy constraint condition (Table 2).

Table 2
Gait Parameters.

	TDC group		USCP group	
	Low accuracy (with cap) Condition	High accuracy (without cap) Condition	Low accuracy (with cap) Condition	High accuracy (without cap) Condition
Speed [m/s] Mean (SD)	1.49 (0.16) * +	1.24 (0.19) * +	1.17 (0.13) * +	0.97 (0.20) * +
Stride length [m] Mean (SD)	1.22 (0.13) * +	1.08 (0.14) +	1.03 (0.19) *	0.99 (0.15)
Min Less affected/ Dom Toe Clearance [cm] Mean (SD)	6.67 (0.71)	6.61 (0.81)	6.79 (0.96) #	6.62 (1.21) #
Min More affected/ Non-Dom Toe Clearance [cm] Mean (SD)	6.61 (0.64) *	6.58 (0.65) *	6.01 (0.79) * #	5.80 (0.84) * #
Step Width [m] Mean (SD)	0.10 (0.01)	0.10 (0.01)	0.11 (0.01)	0.10 (0.01)
Line of progression [cm] Mean (SD)	2.62 (0.61) *	2.88 (0.71) *	4.48 (0.56) * +	3.26 (0.47) * +

Abbreviations: TDC = Typically-developed children; USCP = Unilateral spastic cerebral palsy; SD = Standard deviation; Min = Minimum; Dom = Dominant leg; Non-Dom = none dominant leg, * = $p < 0.05$ USCP group compared with TDC, + = $p < 0.05$ High accuracy condition compared with low accuracy condition, # = $p < 0.05$ Less affected/ Dom side compared with more affected/Non-Dom side.

For upper extremity movement control, children with USCP showed significantly greater differences between the vertical position of the two hands when compared to TDC under both task conditions (Table 3, group: $F_{1,18} = 21.85$, $p < 0.001$). There was also significant group and task condition interaction for the height differences between the two hands (group x task: $F_{1,18} = 5.75$, $p = 0.027$). Post-hoc analyses further indicated that TDC significantly decreased the maximum differences between the heights of the two hands (levelness of the tray) under no cap condition (high accuracy constraints, 30% decreasing) while children with USCP showed no change (2% differences). There were no significant findings between the two groups or two tasks for lateral hand ROM (Table 3, group: $F_{1,18} = 0.32$, $p = 0.57$; task: $F_{1,18} = 0.45$, $p = 0.51$; group x task: $F_{1,18} = 1.43$, $p = 0.25$). For maximum vertical hand ROM, children with USCP had significantly larger vertical ROM than TDC (Table 3, group: $F_{1,18} = 5.86$, $p = 0.026$). Both groups had decreased vertical hand ROM under high accuracy constraint with no group and task interaction (task: $F_{1,18} = 7.90$, $p = 0.012$; group x task: $F_{1,18} = 0.43$, $p = 0.52$). TDC decreased about 14% while children with USCP decreased about 19% under high accuracy constraint condition. Both groups significantly decreased their elbow excursion on both sides under the no cap condition (task: $F_{1,18} = 14.17$, $p = 0.001$). Children with USCP also had significantly larger shoulder excursion on both sides compared to TDC (group: $F_{1,18} = 18.87$, $p < 0.001$).

4. Discussion

Influences of accuracy constraints on gait and bimanual coordination for children with and without USCP were evaluated in the current study using a functional water carrying task. In contrast to our hypotheses that only children with USCP would decrease gait performance and bimanual coordination under higher accuracy constraints, both groups' performances were affected by higher accuracy constraints with no cap on the water bottle. TDC carried the water bottle without a cap steadier than with a cap by decreasing their walking speed, stride length, maximum height differences between the two hands, maximum vertical hand ROM, and elbow joint excursion. Children with USCP coped with higher accuracy constraint condition by decreasing their walking speed, maximum vertical hand ROM, and elbow joint excursion. They also showed decreased lateral deviation in line of progression (less curved path walking) under no cap condition. Interestingly, children with USCP showed similar steadiness of the tray under both high and low accuracy constraint conditions.

TDC children changed their gait performance under the higher accuracy constraint condition of carrying a bottle of water without a cap.

Table 3
Upper Extremity Movement Control.

	TDC group		USCP group	
	Low accuracy (with cap) Condition	High accuracy (without cap) Condition	Low accuracy (with cap) Condition	High accuracy (without cap) Condition
Vertical Hand Difference [cm] Mean (SD)	3.75 (1.21) * +	2.63 (0.69) * +	6.28 (1.92) *	6.43 (2.52) *
Lateral Hand ROM [cm] Mean (SD)	4.49 (1.62)	5.07 (1.64)	5.20 (1.41)	4.96 (1.44)
Vertical Hand ROM [cm] Mean (SD)	4.63 (1.31) * +	3.99 (1.35) * +	6.20 (1.55) * +	5.00(1.45) * +
Less affected/Dom Elbow Excursion [degrees] Mean (SD)	8.62 (4.70) +	7.64 (4.12) +	10.24 (3.56) +	8.23 (2.34) +
More affected/Non-Dom Elbow Excursion [degrees] Mean (SD)	8.78 (4.71) +	7.02 (3.61) +	9.78 (2.41) +	8.21 (2.46) +
Less affected/Dom Shoulder Excursion [degrees] Mean (SD)	10.19 (3.64) *	10.42 (3.76) *	15.77 (4.38) *	17.29 (4.58) *
More affected/Non-Dom Shoulder Excursion [degrees] Mean (SD)	10.28 (2.45) *	10.54 (3.03) *	16.43 (4.57) *	16.18 (2.45) *

Abbreviations: TDC = Typically-developed children; SD = Standard deviation; Dom = Dominant hand; Non-Dom = Non-dominant hand; ROM = range of motion, * = $p < 0.05$ USCP group compared with TDC group, + = $p < 0.05$ High accuracy condition compared with low accuracy condition.

Unlike the previous studies of limited dual task interference [19,21], TDC significantly adjusted their gait performance under higher accuracy constraint condition by reducing their walking speed and stride length during the current tray carrying task. This could mean that the current high accuracy constraint task posed some challenges even for TDC. Thus the current task could be used for general developmental tests of whole body movement control.

In the current study, children with USCP slowed their walking speed under higher accuracy constraints. This finding indicated that the current higher accuracy constraint condition was demanding for children with USCP. Children with USCP were found previously to significantly decrease their walking speed, stride length, step width, and toe clearance under dual task constraints during a box carrying task [19]. In a similar box carrying task, typically-developed young children (4–6 years) and children who were obese or overweight also decreased walking speed and stride length under dual task constraints [22,23]. Correspondingly, children with CP increased performance time during standing and walking while simultaneously performing a secondary cognitive task [21,24].

Interestingly, children with USCP decreased their walking speed without decreasing their stride length under high accuracy constraints. The reason might be that children with USCP already decreased their stride length under dual task constraints of walking and carrying a tray [19], thus further decrease may not be possible with higher accuracy constraints. Without changing the stride length, children with USCP had to decrease their cadence (slowing down the motion) for slower walking speed under higher accuracy constraint condition. Slowing down the movements may require more balance control for children with USCP and could increase risk of fall. In the current study, children with USCP showed lower minimum toe clearance of their more affected legs under both low and high accuracy constraint conditions. Minimum toe clearance has been shown to be related to risk of fall [e.g., 20]. Healthy adults decreased their speed and increased their foot clearance during complex dual task pedestrian obstacles negotiating to prevent tripping [25]. Children with USCP seemed unable to increase their minimum to clearance during the current tasks. Therefore, children with USCP are at a higher risk of fall during these types of dual tasks. Additionally, children with USCP showed better straight line walking under higher accuracy constraints (less lateral deviation in line of progression). The current high accuracy constraint condition of carrying a water bottle without a cap might provide external cues for children with USCP and lead to change in gait performance. External visual focus was found to influence gait performance for children with bilateral CP [26].

Children with USCP also illustrated less bimanual coordination with greater vertical hand ROM and greater height differences between the two hands (less level tray carrying) when compared to TDC under both with and without a cap conditions. In a previous box carrying study, children with USCP showed impaired bimanual coordination when compared to TDC under dual task constraints (without accuracy constraints) as well [6]. Such symmetric bimanual tasks (both hands performed the same movement simultaneously) were found to be mostly unimpaired for children with USCP while seated except when the task complexity increased or required higher accuracy control [14,15]. The current study not only increased the accuracy constraints of the task, it also imposed dual task constraints (carrying the tray and walking). Thus, children with USCP showed impaired bimanual coordination when compared to TDC.

Interestingly, additional accuracy constraints (without a cap) on top of existing dual task constraints (carrying a tray) did not worsen their bimanual coordination performance. That is children with USCP demonstrated similar height differences between the two hands (levelness of the tray), and decreased maximum vertical hand ROM and elbow excursions under higher accuracy constraints. On the other hand, TDC improved their bimanual coordination with decreased height differences between the two hands, less vertical hand ROM, and less elbow excursion under higher accuracy constraint condition (without a cap) in the current study. Although the current water carrying without a cap task imposed additional accuracy constraints, it may also provide external cues to facilitate better bimanual coordination performance for

TDC and for children with USCP to certain extent. External focus of attention has been shown to benefit various movement performances for healthy subjects in previous studies [e.g., 27,28] However, information on external attention focus for children with USCP is limited. More studies will be needed to explore the effects of external attention focus for children with USCP.

5. Clinical relevance

The current tray carrying task is a common school age children activity during lunch. Additional focus should be put on these types of tasks for children with USCP to prevent the possibility of fall. Similar carrying tasks could be used for training or evaluation purpose. Various objects could be placed on the tray to manipulate the task difficulty during training. A cup of water on the tray (external focus of attention) may help the participants improve their tray control. A more complex task such as the current one could be used as a better outcome measure for patients with higher motor capability since simple walking may not detect their improvements.

6. Limitations

While, the current study only had a small group of participants, significant findings were detected using kinematic analyses. Because the complex nature of the current task, only children with mild USCP (MACS levels: I—II, GMFCS levels: I—II) participated in the study. Thus the current findings may not apply to children with greater impaired walking abilities. Due to our limited analyzing capability, only selected joint angles were evaluated while many other joint motions (e.g., trunk motion) could also contribute to the current task. Another limitation of the current study is the lack of direct assessment of EMG for possible muscular co-contraction during high accuracy condition. Future studies evaluating muscular activities will be required to clarify co-contraction issues.

7. Conclusion

It is important to understand movement deficits for children with USCP during activities involving both upper and lower extremities, not separately. Our outcomes indicated that children with USCP had impaired gait performance and bimanual coordination while performing the functional walking and carrying a water bottle with or without a cap tasks when compared to TDC. Gait performances for both groups were affected by higher accuracy constraints. While bimanual coordination was improved under higher accuracy constraints for TDC, only limited change was found for children with USCP. It is exciting to observe that additional accuracy constraints did not further impair dual task performance for children with USCP and even led to better walking straightness. Thus a task similar to current carrying a tray with a water bottle may be applied to whole body assessment or training for children with USCP. Future studies are required to better understand the interferences of various factors on whole body movement control for children with USCP.

Declarations of interest

None

Conflict of interest statement

There are no conflicts of interest associated with this research.

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References

[1] M. Coluccini, E.S. Maini, C. Martelloni, G. Sgandurra, G. Cioni, Kinematic characterization of functional reach to grasp in normal and in motor disabled children, Gait Posture 25 (2007) 493–501.
[2] E. Domellof, B. Rosblad, L. Ronnqvist, Impairment severity selectively affects the control of proximal and distal components of reaching movements in children with hemiplegic cerebral palsy, Dev. Med. Child Neurol. 51 (2009) 807–816.
[3] A.C. Eliasson, A.M. Gordon, H. Forssberg, Tactile control of isometric fingertip forces during grasping in children with cerebral palsy, Dev. Med. Child Neurol. 37 (1995) 72–84.
[4] H. Forssberg, A.C. Eliasson, C. Redon-Zonitenn, E. Mercuri, L. Dubowitz, Impaired grip-lift synergy in children with unilateral brain lesions, Brain 122 (1999) 1157–1168.
[5] A.M. Gordon, J. Charles, S.V. Duff, Fingertip forces during object manipulation in children with hemiplegic cerebral palsy II: bilateral coordination, Dev. Med. Child Neurol. 41 (1999) 176–185.
[6] A.M. Gordon, S.V. Duff, Fingertip forces during object manipulation in children with hemiplegic cerebral palsy. I: anticipatory scaling, Dev. Med. Child Neurol. 41 (1999) 166–175.
[7] B. Steenbergen, E. Van Thiel, W. Hulstijn, R.G.J. Meulenbroek, The coordination of reaching and grasping in spastic hemiparesis, Hum. Mov. Sci. 19 (2000) 75–105.
[8] B. Steenbergen, W. Hulstijn, A. De Vries, M. Berger, Bimanual movement coordination in spastic hemiparesis, Exp. Brain Res. 110 (1996) 91–98.
[9] J. Charles, A.M. Gordon, Development of hand-arm bimanual intensive training (HABIT) for improving bimanual coordination in children with hemiplegic cerebral palsy, Dev. Med. Child Neurol. 48 (2006) 931–936.
[10] Y.C. Hung, J. Charles, A.M. Gordon, Bimanual coordination during a goal-directed task in children with hemiplegic cerebral palsy, Dev. Med. Child Neurol. 46 (2004) 746–753.
[11] Y.C. Hung, J. Charles, A.M. Gordon, The influence of task constraints in bimanual coordination for children with hemiplegic cerebral palsy, Exp. Brain Res. 201 (2010) 421–428.
[12] B. Steenbergen, J. Charles, A.M. Gordon, Fingertip force control during bimanual object lifting in hemiplegic cerebral palsy, Exp. Brain Res. 186 (2008) 191–201.
[13] A. Utley, B. Steenbergen, D.A. Sugden, The influence of object size on discrete bimanual co-ordination in children with hemiplegic cerebral palsy, Disabil. Rehabil. 26 (2004) 603–613.
[14] D. Sugden, A. Utley, Interlimb coupling in children with hemiplegic cerebral palsy, Dev. Med. Child Neurol. 37 (1995) 293–309.
[15] A. Utley, D. Sugden, Interlimb coupling in children with hemiparetic cerebral palsy during reaching and grasping at speed, Dev. Med. Child Neurol. 40 (1998) 396–404.
[16] S.M. Bruijn, M. Millard, L. van Gestel, P. Meyns, I. Jonkers, K. Desloovere, Gait stability in children with cerebral palsy, Res. Dev. Disabil. 34 (2013) 1689–1699.
[17] V. Cimolin, M. Galli, N. Tenore, G. Albertini, M. Crivellini, Gait strategy of uninvolved limb in children with spastic hemiplegia, Eur. J. Phys. Rehabil. Med. 43 (2007) 303–310.
[18] M. Galli, V. Cimolin, C. Rigoldi, N. Tenore, G. Albertini, Gait Patterns in hemiplegic children with Cerebral Palsy: comparison of right and left hemiplegia, Res. Dev. Disabil. 31 (2010) 1340–1345.
[19] Y.C. Hung, G.S. Meredith, Influence of dual task constraints on gait performance and bimanual coordination during walking in children with unilateral cerebral palsy, Res. Dev. Disabil. 35 (2014) 755–760.
[20] T. Killeen, C.S. Easthope, L. Demko, L. Fillli, L. Lorincz, M. Linnebank, A. Curt, B. Zorner, M. Bolliger, Minimum toe clearance: probing the neural control of locomotion, Sci. Rep. 7 (2017), https://doi.org/10.1038/s41598-017-02189-y.
[21] M. Katz-Leurer, H. Rotem, S. Meyer, Effect of concurrent cognitive tasks on temporo-spatial parameters of gait among children with cerebral palsy and typically developed controls, Dev. Neurorehabil. 17 (2014) 363–367.
[22] Y.C. Hung, S.V. Gill, G.S. Meredith, Influence of dual task constraints on whole body organization during walking in children who are overweight and obese, Am. J. Phys. Med. Rehabil. 92 (2013) 461–467.
[23] Y.C. Hung, G.S. Meredith, S.V. Gill, Bimanual and whole body organization during walking, Gait Posture 38 (2013) 450–454.
[24] D.S. Reilly, M.H. Woollacott, P. van Donkelaar, S. Saavedra, The interaction between executive attention and postural control in dual-task conditions: children with cerebral palsy, Arch. Phys. Med. Rehabil. 89 (2008) 834–842.
[25] S. Licence, R. Smith, M.P. McGuigan, C.P. Earnest, Gait pattern alterations during walking, texting and walking and texting during cognitively distractive tasks while negotiating common pedestrian obstacles, PLoS One 10 (2015) e0133281.
[26] A. Bartonek, C.M. Lidbeck, E.M. Gutierrez-Farewik, Influence of external visual focus on gait in children with bilateral cerebral palsy, Pediatr. Phys. Ther. 28 (2016) 393–399.
[27] R. Abdollahipour, G. Wulf, R. Psotta, M. Palomo Nieto, Performance of gymnastics skill benefits from an external focus of attention, J. Sports Sci. 33 (2015) 1807–1813.
[28] E.C. Kal, J. van der Kamp, H. Houdijk, External attentional focus enhances movement automatization: a comprehensive test of the constrained action hypothesis, Hum. Mov. Sci. 32 (2013) 527–539.