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Influence of dual task constraints during walking for children

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ABSTRACT

The effects of dual-task constraints on bimanual coordination and walking in three age groups: young (4–6 years old), middle (7–9 years old), and older groups (10–13 years old) were examined. Children were asked to first walk along a path (baseline condition) and then to walk along the same path while carrying a box steady and level (dual-task condition). The young group showed less bimanual coordination with less level and more variable normalized vertical box positioning (mean hand differences, young: 3.68%, middle: 2.42%, older: 1.61%), less correlated hand movements (mean correlation, young: $r(8) = 0.58$, middle: $r(8) = 0.77$, older: $r(8) = 0.79$), and more elbow and shoulder joint excursion on the dominant side (all $Ps < 0.05$). In addition, the young group had shorter stride lengths and less normalized anterior/posterior ground reaction forces under the dual-task condition than the baseline condition (all $Ps < 0.05$). These findings indicate that 4- to 6-year-old children might still be developing their ability to perform activities requiring dual-task constraints that involve simultaneous use of the upper and lower extremities.

1. Introduction

Functional activities like carrying large objects involve skilled bimanual coordination (i.e., using two hands to perform a task). The ability to use both hands to perform tasks is central to markers indicative of children's development; bimanual coordination is associated with the risk of neuromotor delay and rehabilitation outcomes for intervention. Most daily activities require skilled bimanual coordination to complete functional tasks. However, most functional activities are not performed in isolation; they involve dual-task constraints, which require completing more than one action at the same time. For example, carrying large objects steady and level while walking involves both bimanual coordination and controlled gait.

Performing activities that require dual task constraints can pose motor challenges for children. Children's gait becomes adult-like around 4–6 years old [1,2]: overlapping with improvements in bimanual coordination [3]. Bimanual coordination in typically developing children begins to improve at 5 years old [3] and continues improving until 15 years old [4]. There are two types of bimanual coordination. Symmetrical bimanual coordination requires using both hands to perform similar movements (e.g., lifting a large object with both hands), while asymmetrical bimanual coordination requires using both hands to perform different movements during the task (e.g., cutting food with a knife while stabilizing it with a fork). For children, symmetrical bimanual coordination develops prior to asymmetrical bimanual coordination [5], possibly due to a reduced need for motor planning with symmetrical tasks [6] or continued development in the corpus callosum [7]. Therefore, younger children would be expected to perform symmetrical bimanual tasks more easily than asymmetrical bimanual tasks. Children's developing skills are reflected in how they perform tasks; when performing a cognitive task while walking, 4–6 year olds alter their gait [8,9]. The effect also seems to be greater in younger versus older children; under dual task constraints, postural control affects 5–6 year olds, but not 7–16 year olds [10]. Therefore, examining the effects of dual-task constraints involving upper and lower extremities may provide an opportunity to understand bimanual coordination and gait development in children.

Despite the effect of children's developing bimanual and gait abilities on performing functional activities, few studies have examined upper and lower extremity functioning in typically developing children during functional activities. Kinetic and kinematic measures of upper or lower extremity asymmetry have been associated with pathological conditions [e.g., 11–15]. For example, children with hemiplegia have impaired bimanual coordination [11] and impaired gait [e.g., 16,17]. In typically developing children, most research either studies upper [e.g., 18–20] or lower extremity control [e.g., 21] in isolation. Therefore, we have limited information about the

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interaction of upper and lower extremity control in typically developing children as they perform functional activities.

In the present study, we investigated the influence of dual-task constraints on bimanual coordination and gait in typically developing children in young (4–6 years old), middle (7–9 years old), and old (10–13 years old) age groups. In a dual-task condition, they walked while performing a functional task: carrying an unloaded box. The purpose of the study was two-fold: (1) to examine the effects of dual task constraints on children's bimanual coordination and gait and (2) to investigate whether children's performance differed according to age (i.e., young, middle, or old). We hypothesized that during the dual task condition the young group would: (1) show less bimanual coordination than the other groups via asymmetry during a task requiring symmetrical movements and (2) show changes in gait to accommodate the higher demands of a dual-task activity.

2. Methods

2.1. Participants

Twenty-four children between 4 and 13 years old, recruited through community flyers in the New York area, participated in this study. Children were divided into three age groups, young (4–6 years), middle (7–9 years), and older (10–13 years) ages to examine differences in performance when bimanual coordination and gait are still developing to when they become more refined. Inclusion criteria for participation included: (1) normal cognitive abilities (mainstreamed in school) and (2) no known physical disabilities or conditions that precluded independent walking. We included both left and right-handed children in the study. However, we required that left handed children be older than 5 years old because left and right handed children seem to perform equally well on activities that involve bimanual coordination after 5 years old [22]. Descriptive information for each child is shown in Table 1. Informed consent was obtained from all participants and their caregivers, and the study was approved by the University Institutional Review Board.

2.2. Experimental

Participants walked on a 406.4 cm-long flat path with two AMTI OR6-6 force platforms (each 46 cm × 50 cm) embedded in the floor in the middle of path. For the box carrying task (dual task constraint condition), participants carried an empty plastic box (length: 45 cm, width: 29 cm, height: 17 cm). We chose to use an empty rather than a weighted box to eliminate the possibility of fatigue affecting children's performance. For the walking task (baseline condition), participants walked on the flat path without carrying anything.

2.3. Procedure

Participants were asked to walk on the flat path following an auditory go-signal. During the dual task condition, they were instructed to walk while holding the box steady and level without allowing the box to touch their body with their elbows flexed at right angles. The box was placed in their hands to ensure consistent hand, elbow, and shoulder joint positioning. To ensure that children understood the task, an example of the correct posture required was given both with verbal instruction and demonstration. Each trial ended after they walked to a stop line at the end of the path. Three practice trials were given prior to five collected trials to allow participants to become familiar with the task. The baseline condition (five walking trials) was performed prior to the dual task condition to avoid possible residual effects from walking with the box. If a trial was not collected successfully (e.g., the box touched the body), the participant was asked to redo the trial. Values from all 10 collected trials were averaged for each child for further analyses.

2.3.1. Data acquisition

Three-dimensional kinematic data were collected using the whole body plug-in-gait model of VICON Nexus 1.51 with seven infrared cameras. Forty-one reflective markers were placed 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, each tibia, the ankle joints, the heels and the big toes. Markers were also placed between the clavicles, on the sternum, on C7, on T10, and on the right scapula. All markers were digitized at a rate of 120 Hz with VICON Nexus 1.51. All digitized signals were processed with a low pass digital filter with a cutoff frequency of 6 Hz. Kinetic data from both force plates were processed and synchronized with the kinematic data at a rate of 1200 Hz with VICON Nexus 1.51.

2.4. Analyses

Example kinematic hand and heel traces from all three age groups are shown in Fig. 1. Basic measures of gait and bimanual coordination were chosen to examine spatial and temporal symmetry between upper extremities while carrying a box and lower extremities during walking. The gait cycle was defined from heel strike to heel strike of the same foot and began with one foot strike on the first force plate. For general gait parameters, stride length, velocity, percentage of the stance phase, and highest foot clearance (i.e., highest height of the foot's vertical position) during gait were calculated for each trial and were compared between age groups. For the upper extremities, vertical position (z) difference between the two hands, correlation between the vertical position of the two hands, and full elbow and shoulder joint excursion (maximum joint angle minus minimum joint angle during a gait cycle while holding a box) in the sagittal plane were measured to evaluate bimanual coordination. The maximum anterior–posterior, lateral, and vertical forces were evaluated to understand force control of the foot during gait between the

Table 1
Participant characteristics.

	Mean age y, m (SD m)	Dominantside	Height in cm (SD)	Weight in kg (SD)	Leg length in cm (SD)
Young	5, 2 (8)	Right ($n=7$) Left ($n=1$)	118 (8.8)	21 (4.7)	57 (4.3)
Middle	8, 3 (9)	Right ($n=7$) Left ($n=1$)	135 (7.1)	37 (12.0)	68 (4.8)
Old	11, 6 (12)	Right ($n=6$) Left ($n=2$)	156 (14.1)	46 (8.9)	84 (7.5)

SD: standard deviation; m: month; y: year.

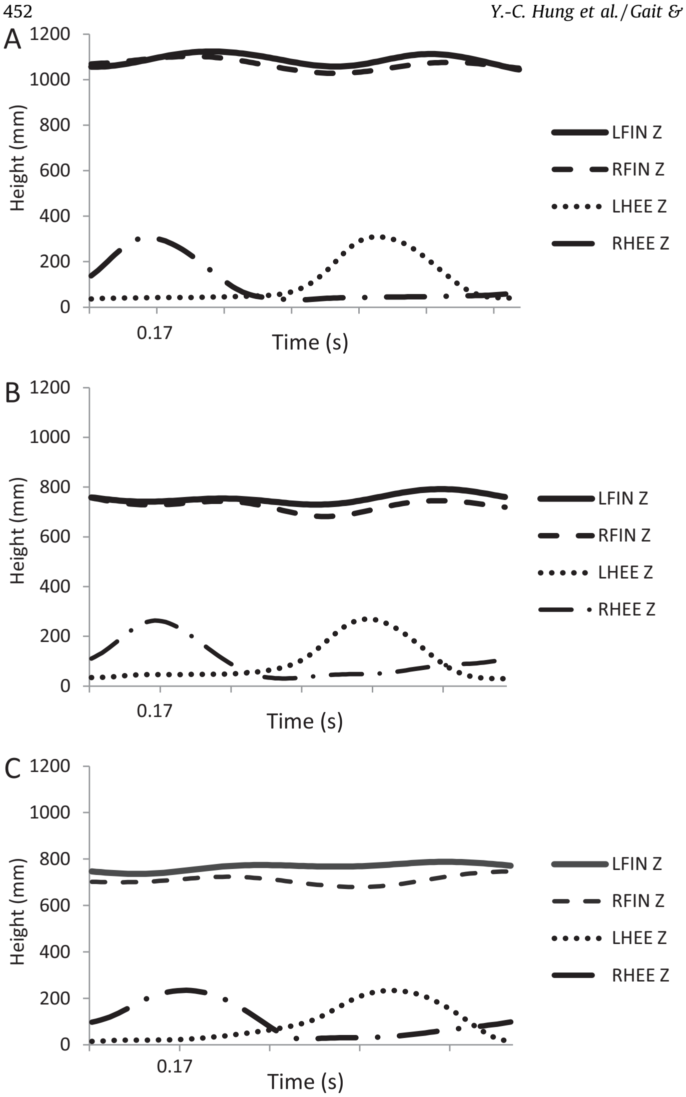

Fig. 1. One gait cycle with left foot to left foot heel strike. (A) Kinematic traces of a 13-year-old child. (B) Kinematic traces of an 8-year-old child. (C) Kinematic traces of a 4 year-old-child. Left hand (marker on index MCP joint) vertical position: LFIN Z; right hand vertical position: RFIN Z; left heel vertical position: LHEE Z; right heel vertical position: RHEE Z.

two conditions. To take into account physical growth (height and weight) between the age groups, stride length, highest foot clearance and vertical hand position difference were normalized to each child's height and forces were normalized to weight. Velocity was normalized to both height and weight of each child. Variability for all measures were calculated using normalized measure of dispersion – coefficient of variation (standard deviation divided by mean) for all the subjects to better understand movement control.

Repeated measure ANOVAs with one between factor (3 groups) and one within factor (2 tasks) were performed on all measures of general gait parameters and force measures. As determined using Levene's test, assumptions of homogeneity of variance and sphericity were met. A one-way ANOVA was done on upper extremity measures with one group factor for three age groups. Post hoc comparisons were carried out using the Tukey procedure. Statistical significance was set at $p < 0.05$.

3. Results

3.1. General gait parameters

The young group showed differences in gait when walking under dual-task and baseline conditions. Table 2 shows that the average stride lengths for the young group decreased significantly from walking to box carrying while the middle and older groups maintained their stride lengths between walking tasks (group × task, $F_{2,21} = 6.28$, $\eta^2 = 0.37$, $p = 0.007$). No differences were found for the normalized stride lengths between the three groups (group, $F_{2,21} = 0.06$, $\eta^2 = 0.01$, $p = 0.94$). The young group also had the highest variability in stride length among the three groups (group, $F_{2,21} = 5.55$, $\eta^2 = 0.35$, $p = 0.012$). No significant differences were found between groups and tasks for velocity (group, $F_{2,21} = 0.36$, $\eta^2 = 0.03$, $p = 0.57$; task, $F_{1,21} = 0.55$, $\eta^2 = 0.03$, $p = 0.47$). Similarly, the percentage of the stance phase was not different between groups and tasks (group, $F_{2,21} = 1.77$, $\eta^2 = 0.14$, $p = 0.20$; task, $F_{1,21} = 0.002$, $\eta^2 = 0.00$, $p = 0.97$). The young group had the highest normalized foot clearance (normalized heel z position) among the three groups (Table 2, group, $F_{2,21} = 4.10$, $\eta^2 = 0.28$, $p = 0.031$). No difference was found for foot clearance between the two tasks (task, $F_{1,21} = 0.35$, $\eta^2 = 0.02$, $p = 0.56$). The young group also showed the highest variability of foot clearance among the groups (group, $F_{2,21} = 4.07$, $\eta^2 = 0.28$, $p = 0.032$).

Table 2
Gait.

	Young		Middle		Old	
	Baseline condition	Dual task condition	Baseline condition	Dual task condition	Baseline condition	Dual task condition
Normalized stride length [%] (SD)	0.85 (0.02)[+]	0.80 (0.02)[+]	0.82 (0.02)	0.83 (0.02)	0.84 (0.02)	0.84 (0.02)
CV of stride length	0.07[*]	0.06[*]	0.06[*]	0.04[*]	0.03[*]	0.03[*]
Normalized velocity [cm/s/kg cm] (SD)	0.03 (0.003)	0.03 (0.003)	0.03 (0.003)	0.03 (0.003)	0.02 (0.003)	0.03 (0.003)
Stance phase [%] (SD)	51.52 (5.95)	52.71 (4.59)	53.02 (7.94)	54.14 (4.69)	57.19 (2.78)	54.84 (6.44)
Normalized heel z position [%] (SD)	17.49 (1.37)[*]	17.64 (1.52)[*]	16.87 (0.98)[*]	16.91 (1.21)[*]	15.98 (0.78)[*]	16.03 (0.84)[*]
CV of heel z position	0.04[*]	0.04[*]	0.03[*]	0.03[*]	0.03[*]	0.02[*]
Vertical NGF (SD)	1.42 (0.24)[*]	1.41 (0.31)[*]	1.18 (0.11)[*]	1.24 (0.12)[*]	1.18 (0.05)[*]	1.22 (0.05)[*]
CV of vertical GF	0.14[*]	0.15[*]	0.08[*]	0.06[*]	0.04[*]	0.03[*]
Medial/lateral NGF (SD)	0.10 (0.04)	0.09 (0.03)	0.08 (0.02)	0.09 (0.01)	0.08 (0.01)	0.08 (0.01)
CV of medial/lateral GF	0.24	0.30	0.18	0.24	0.19	0.24
Anterior/posterior NGF (SD)	0.31(0.13)[*,+]	0.23 (0.12)[*,+]	0.21 (0.04)[*]	0.23 (0.02)[*]	0.21 (0.02)[*]	0.22 (0.02)[*]
CV of anterior/posterior GF	0.18[*,+]	0.25[*,+]	0.11[*]	0.12[*]	0.10[*]	0.08[*]

SD: standard deviation; CV: coefficient of variation; NGF: normalized ground reaction force.
[*] $p < 0.05$ three age group difference.
[+] $p < 0.05$ baseline condition compared with dual task condition.

3.2. Upper extremity movement during walking

Traces in Fig. 1 are reflective of the young group; children in the young group had a larger deviation between the two hands (vertical position difference) than the older children. The normalized maximum vertical position differences between the two hands among the three age groups are shown in Table 3. The young group had significantly higher normalized maximum vertical position differences between the two hands when compared with the other two groups indicating that the box was more tilted during walking (group, $F_{2,21}$ = 15.38, p = 0.001). Additionally, the young group had the highest variability for normalized maximum vertical position differences between the two hands (Table 3, group, $F_{2,21}$ = , p = 0.025). The young group also showed the lowest correlation between the vertical positions of the two hands during a gait cycle among the three groups (Table 3, group, $F_{2,21}$ = , p = 0.025).

Table 3 illustrates average dominant side elbow and shoulder joint excursion while carrying the box during walking. The young group had significantly larger joint excursion than the other groups for both elbow and shoulder joints on the dominant side. The older group had smaller joint excursion than the other two groups for both elbow and shoulder joints on the dominant side (group, elbow, $F_{2,21}$ = 6.16, p = 0.008; shoulder, $F_{2,21}$ = 3.51, p = 0.048). Interestingly, there was no significant difference between the three age groups in elbow and shoulder joint excursion on the non-dominant hand (group, elbow, $F_{2,21}$ = 2.50, p = 0.11; shoulder, $F_{2,21}$ = 1.25, p = 0.31).

3.3. Force

Table 2 shows the normalized maximum anterior/posterior ground reaction force of the foot during a gait cycle. The young group decreased normalized anterior/posterior ground reaction force while the middle and older group showed no change in force from walking to box carrying (group × task, $F_{2,21}$ = 21.46, η^2 = 0.67, p = 0.001). Among the three age groups, the young group had the highest normalized maximum foot anterior/posterior force, and the old group had the least normalized force (group, $F_{2,21}$ = 6.40, η^2 = 0.38, p = 0.007). The young group also had more variable normalized anterior/posterior force control than the middle and older groups (group, $F_{2,21}$ = 25.34, η^2 = 0.71, $p < 0.001$), and more variability under dual-task condition than the baseline walking condition (task, $F_{1,21}$ = 10.64, η^2 = 0.35, p = 0.004). The young group had the highest normalized maximum ground reaction vertical force among the three groups (group, $F_{2,21}$ = 6.16, η^2 = 0.38, p = 0.008), and the young group also showed the highest variability in normalized maximum vertical force control (group, $F_{2,21}$ = 9.75, η^2 = 0.49, p = 0.001). For normalized maximum foot medial/lateral force and its variability during a gait cycle, there were no significant differences between the tasks or groups.

4. Discussion

The primary purpose of this study was to evaluate effects of dual-task constraints on gait and bimanual coordination in children ages 4–13 years old. Among three age groups, the young group (4–6 years old) showed less bimanual coordination compared to the middle and old group. They demonstrated a decreased ability to maintain a level box, less correlated hand movements, and had more joint excursion in the elbow and shoulder joints on the dominant side. The young group also showed more variable hand movement than the middle and older groups. Gait control of the young group was also affected by dual-task constraints. The young group decreased normalized stride lengths and decreased normalized anterior/posterior ground reaction force in the dual-task condition. The young group also showed more variable anterior/posterior ground reaction force control when walking with a box compared to baseline.

4.1. Bimanual coordination

Our results suggest that younger children may still be developing the ability to coordinate both hands while carrying objects. We found that the young group (4–6 years old) showed the least bimanual coordination ability during our dual-task condition. Given that this task required symmetrical movements, the young group was unable to keep the box level during walking and both hands moved in a less coordinated manner. Although the literature suggests that children in this age group can perform bimanual tasks such as tapping or tracing [23], the added dual task constraint requirement may have increased the difficulty of the task for children. Our finding that the young group had increased movement variability compared to the other groups indicates that the task was more difficult for them [24,25]; early motor skill acquisition is often characterized by more variability in motor movements compared to later skill acquisition [26]. The dual task condition used in the current study may be useful in clinical settings to simultaneously assess upper and lower extremity movements during a functional task. The complexity of the task would also allow for an examination of bimanual coordination, postural control, and dual-task attentional abilities. Currently, most clinical assessments are limited to testing either upper or lower extremity function in isolation.

Hand dominance may have played a role in our results. Our findings showed that the young group had greater elbow and shoulder joint excursion on their dominant side compared to the non-dominant side. The dominant hand sometimes plays a leading role during symmetrical non-functional bimanual tasks [e.g., 27,28], but most often takes the lead during asymmetrical tasks. Differentiating when it is necessary for the dominant hand to take the lead may require experience as well as neurological maturity, which young children may still be developing.

4.2. Gait

As indicated previously, children around 4- to 6-years-old develop a more adult-like gait based on kinematic and kinetic measures [1,2]. In the current study, the young group decreased their stride lengths under dual-task constraints while both the middle and

Table 3
Upper extremity movement.

	Young		Middle		Old	
	Dom	Non-dom	Dom	Non-dom	Dom	Non-dom
Normalized vertical hand difference [%] (SD)	3.68 (1.01)*		2.42 (0.52)*		1.61 (0.44)*	
CV of vertical hand difference	0.38*		0.28*		0.31*	
Two hands correlation (SD)	0.58 (0.17)*		0.77 (0.11)*		0.79 (0.10)*	
Elbow excursion [degrees] (SD)	6.70 (2.82)*	6.54 (3.88)	4.94 (1.25)*	4.68 (1.42)	3.28 (0.93)*	3.99 (1.11)
Shoulder excursion [degrees] (SD)	10.22 (4.83)*	9.17 (4.49)	7.63 (0.93)*	7.79 (1.08)	6.29 (1.76)*	6.77 (2.34)

SD: standard deviation; CV: coefficient of variation; dom: dominant; non-dom: non-dominant.
* $p < 0.05$ three age group difference.

older groups were able to maintain their stride length. Two reasons may account for the differences in young children's strides between conditions. First, both 15-month-old infants [29] and 7-year-old children [30] tend to decrease the length of their steps when a change in the environment makes tasks more challenging, presumably to adopt a more cautious gait pattern to avoid falling. Second, during dual task constraints, previous studies have demonstrated that walking while performing a second task (either cognitive or postural in nature) causes a reduction in stride length especially for 4- to 6-year olds [8–10]. This change in gait may indicate that younger children have limited attentional resources to control gait while performing a secondary task [10]. Therefore, shorter stride lengths for the young group could indicate that carrying the box during walking was more challenging for them. Our findings that young children decrease anterior/posterior ground reaction forces and increase variability in the dual-task condition also supports the idea that the dual task condition posed challenges for them. Since anterior/posterior ground reaction forces are used to propel the foot forward, shorter stride length for young children in the dual-task condition would require less anterior/posterior propulsion force. This could serve to limit foot range of motion and freeze degrees of freedom (i.e., stiffen some joints while performing the skill). Limiting degrees of freedom has been linked with early skill acquisition during motor learning secondary to increased task difficulty. Thus, the difficulty and high attentional demands of the current dual-task constraint may have been reflected in altered gait for 4–6 year olds.

5. Conclusions

The current study highlights the differences in younger (4- to 6-years-old) and older (7- to 14-years old) children's ability to perform tasks under dual-task constraints. Younger children show decreased bimanual coordination and modified gait control under dual-task conditions compared to baseline. Children 4–6 years old may still be developing the ability to cope with dual-task constraints. The box carrying task may be a useful tool to assess children's bimanual coordination and gait control under dual-task constraints while performing a functional task. Rehabilitation protocols that involve assessing either upper extremity coordination, lower extremity control, or both might be able to incorporate the current task for use with their clients.

Conflict of interest statement

There are no conflicts of interest.

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