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RESEARCH ARTICLE

Influence of accuracy constraints on bimanual coordination during a goal-directed task in children with hemiplegic cerebral palsy

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Abstract Previously we found that children with hemiplegic cerebral palsy (CP) have impaired bimanual coordination compared to typically developing children during a functional drawer-opening task. However, performance of the task under time constraints (fast-as-possible) facilitated better bimanual coordination for these children. Accuracy is another important task constraint that could influence the coordination of the two hands during such tasks. The effect of accuracy constraints on bimanual coordination in children with hemiplegic CP is not well understood. In the present study, children were asked to reach forward and open a drawer with one hand and then activate a light switch inside the drawer with the contralateral hand. Task accuracy constraints (different handles and switch sizes) were manipulated in order to determine their effect on upper extremity coordination. Eleven children with hemiplegic CP (age 8–16 years) and eleven age-matched typically developing children participated in this study. The results show that higher accuracy constraints prolong the total movement completion time for both groups of children. However, children with hemiplegic CP demonstrated less sequential movement with a higher accuracy constraint (a smaller knob handle) than a lower accuracy constraint (a larger loop handle). Nevertheless, presentation of both higher accuracy constraints (handle and switch) at the same time was detrimental to their performance. These influences of task constraints were similar regardless of which hand was used to open the drawer. The results suggest that performance may not be linearly related to the constraints, and in some cases "more is not better".

Introduction

Children with hemiplegic cerebral palsy (CP) have early non-progressive lesions of the developing brain that result in a number of impairments predominantly on one side of the body. The associated unimanual movement deficits of the involved hand have been documented extensively (e.g., Twitchell 1958; Brown et al. 1989; Eliasson et al. 1991, 1992, 1995; Steenbergen et al. 1998; Forssberg et al. 1999; Gordon et al. 1991, 1999, 2003; Gordon and Duff 1999a, b; Wright et al. 2001). However, since most activities of daily living require both hands (e.g., dressing, opening a bottle), increased understanding of bimanual coordination is essential.

Several studies have investigated bimanual coordination in children with hemiplegic CP (Sugden and Utley 1995; Steenbergen et al. 1996, 2000, 2008; Utley and Sugden 1998; Volman et al. 2002; Hung et al. 2004; Utley et al. 2004; see Gordon and Steenbergen 2008). During symmetrical, bimanual reaching tasks, children with hemiplegic CP showed the ability to coordinate their bimanual movements by compensating with their non-involved hand as long as the accuracy demands or task complexity were not increased (Sugden and Utley 1995; Steenbergen et al.

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1996, 2000; Utley and Sugden 1998). Utley et al. (2004) also found strong temporal coupling between the two hands when reaching and grasping cubes symmetrically. But in contrast to the above findings, the participants in this study not only were able to maintain temporal coupling with smaller cubes (higher accuracy demands), but also demonstrated better spatial and postural coupling of the two hands. Utley et al. (2004) suggested that the differences in their finding compared to the previous studies might be related to the contextual familiarity of their task. Thus, the context and constraints of the task may play a critical role in bimanual coordination even within the domain of a symmetric bimanual task.

A functional, asymmetric drawer-opening task has been used to investigate bimanual coordination for monkeys with and without cerebral lesions (Wiesendanger 1994, 1993; Kazennikov et al. 1994, 1998) and healthy human subjects (Perrig et al. 1999; Kazennikov et al. 2002). These studies demonstrated a high degree of bimanual coupling even when vision or sensory information were blocked. In a similar task, children with hemiplegic CP were found to be less coordinated, with reduced movement overlap of the two hands and sequential completion of opening the drawer and manipulating its contents compared to typically developing children (Hung et al. 2004). Performance of the task under time constraints (fast-as-possible) facilitated better bimanual coordination for these children. Accuracy is another important task constraint that could influence the coordination of the two hands during such tasks. However, the influence of changing accuracy demands on the coordination of the two hands during a functional asymmetrical task (i.e., drawer opening) is not known. Given that goal-directed functional movements are performed in various environments in everyday life, each with its own set of unique constraints, understanding the influence of these constraints on movement coordination is important.

In the present study we manipulated the task constraints of the draw-opening hand (handle) and the task hand (drawer contents) and the role of the two hands to determine the effect of accuracy constraints on bimanual coordination in children with hemiplegic CP. We hypothesized that children with hemiplegic CP will demonstrate impaired bimanual coordination, and that their performance will be affected by accuracy demands to a greater extent than typically developing age-matched children.

Methods

Participants

Eleven children with hemiplegic CP (8–16 years, 6 males, 5 females) and 11 age-matched typically developing right-handed children (8–16 years, 6 males, 5 females) participated in this study. Handedness of the age-matched children was determined using the Edinburgh Handedness Inventory (mean L.Q. = 79.6, Oldfield 1971). Static two-point discrimination, hand strength, pinch strength and the Jebsen–Taylor test of Hand Function (without the writing subtest) for children with hemiplegic CP are shown in Table 1. Written informed consent was obtained from all participating children and their parents, and the study was approved by the Institutional Review Board at Queens College, CUNY and Teachers College, Columbia University.

Experimental setup

Participants were seated and asked to open a spring-loaded drawer (load 0.3 kg) with one hand (drawer hand) and to insert their contralateral hand (task hand) in the drawer to activate a push-button light switch (Fig. 1A). At the starting position, each child sat 15 cm in front of the table with their elbows flexed at right angles and hands positioned 30 cm apart at the edge of the table. The drawer (15 × 15 cm) was placed in front of the subject at midline 30 cm from the edge of the table. An exchangeable handle, either a loop (9 cm in length and 3 cm in depth, requiring hooking digits through to pull) or a knob (3.5 cm in diameter and 3 cm in depth, requiring digit-to-thumb opposition; i.e., greater accuracy), was attached to the front of the drawer to vary the grasp precision required for the drawer hand. Either a “large” (14 × 10 cm) or a “small” (1.5 × 2 cm) push-button light switch was placed inside the drawer to manipulate the accuracy demands of the task hand.

Procedure

Participants were asked to reach forward and open the drawer with one hand and activate the light switch inside the drawer with the contralateral hand following an auditory start-signal. Each trial ended when the light switch inside the drawer was activated. The task was performed with each of the two handles (knob, loop), with each of the two switches (small, large), and with each hand opening the drawer (involved/non-dominant, non-involved/dominant) (i.e., 8 conditions) at a fast-as-possible speed. After three practice trials, five trials were collected for each condition; i.e., a total of 40 trials. All of the conditions were randomized for each pair of children (one child with hemiplegic CP and one age-matched child). Rest periods between the conditions were provided at the participants’ request.

Data acquisition

3-D kinematic movement data were collected with four infrared cameras placed in front of the participants.

Table 1 Description of subjects

Average group results	Age (years)	Jebsen–Taylor test (max. 720 s)		Two-point discrimination (mm)		Hand strength (kg)		Pinch strength (kg)	
		I/ND	NI/D	I/ND	NI/D	I/ND	NI/D	I/ND	NI/D
With CP	13.1	231.0	52.1	3.9	2.6	7.4	23.5	2.0	5.1
SD	2.6	142.5	16.0	1.1	0.7	5.4	7.4	1.4	1.9
Control	12.8	43.5	35	2.2	2.2	24.9	26.5	5.3	6.2
SD	2.8	17.7	7.7	0.4	0.4	9.9	11	1.4	2.0

Two-point discrimination values represent average of thumb, index and middle finger

I Involved hand, *Non*-I non-involved hand

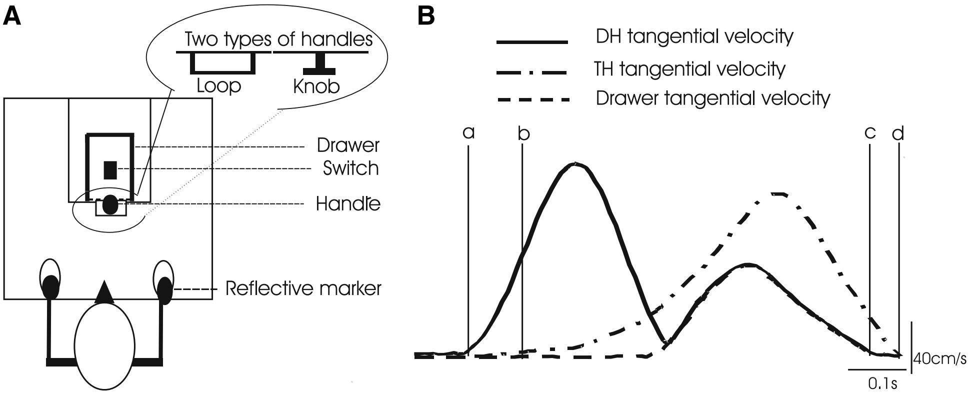

Fig. 1 **A** Experimental setup with a loop or a knob handle (*inset*). **B** Kinematic traces of the hands and the drawer of a representative subject. *a* Onset of movement for the drawer hand (*DH*), *b* onset of movement for the task hand (*TH*), *c* movement offset of the drawer hand when the drawer is completely opened, and *d* movement offset of the task hand. Note that the drawer tangential velocity trace is partially obscured by the drawer hand tangential velocity trace

Reflective markers were placed on the mid-point of the bilateral wrist and one on the drawer. All markers were digitized at a rate of 120 Hz with Eva 5.36 (Motion Analysis Corporation) kinematic software. All digitized signals were processed through a digital low pass filter (6 Hz).

Analysis

Example kinematic traces from the two hands and the drawer of a typically developing child are shown in Fig. 1B. Tangential velocity of each marker was calculated based on the instantaneous three-dimensional change of the marker position over time (1/120 s). The onset of hand movement (Fig. 1B, a, b) was defined when the wrist tangential velocity reached a criterion of 2.6 cm/s and constantly moved forward thereafter. Similarly, the end of drawer opening (Fig. 1B, completely open, c) was defined as drawer velocity below 2.6 cm/s. Since most of the children combined the reach and the activation of the switch movements while the task hand was inserted in the drawer (activated the switch with high velocity), the task hand offset time (Fig. 1B, d) was defined as the time either when the wrist tangential velocity fell below the same criterion of 2.6 cm/s or when the hand activated the light switch inside the drawer.

Three temporal measures were used to examine bimanual coordination. First, we measured the overall *task completion time*, which was defined by the time between the onset of the drawer hand and the offset of the task hand (Fig. 1B, a–d). Second, the *goal synchronization* of the two hands was measured, which was defined by the time difference between the drawer hand fully opening the drawer and the task hand reaching inside the drawer (Fig. 1B, c, d). Finally, the normalized *movement overlap* time was measured, which was defined by the overlap of movement time of their two hands (Fig. 1B, b, c) as a percentage of the total task completion time. In order to determine whether the two types of accuracy constraints (handles and switches) affected the movement of each hand, we also measured the movement time of the drawer hand (Fig. 1B, a–c) and the task hand (Fig. 1B, b, d).

A 2 (group) × 2 (hand) × 2 (handle) × 2 (switch) ANOVA with repeated measures on the last three factors were performed on all measures. Post hoc comparisons were carried out using the Tukey procedure. Statistical significance was set at $P < 0.05$.

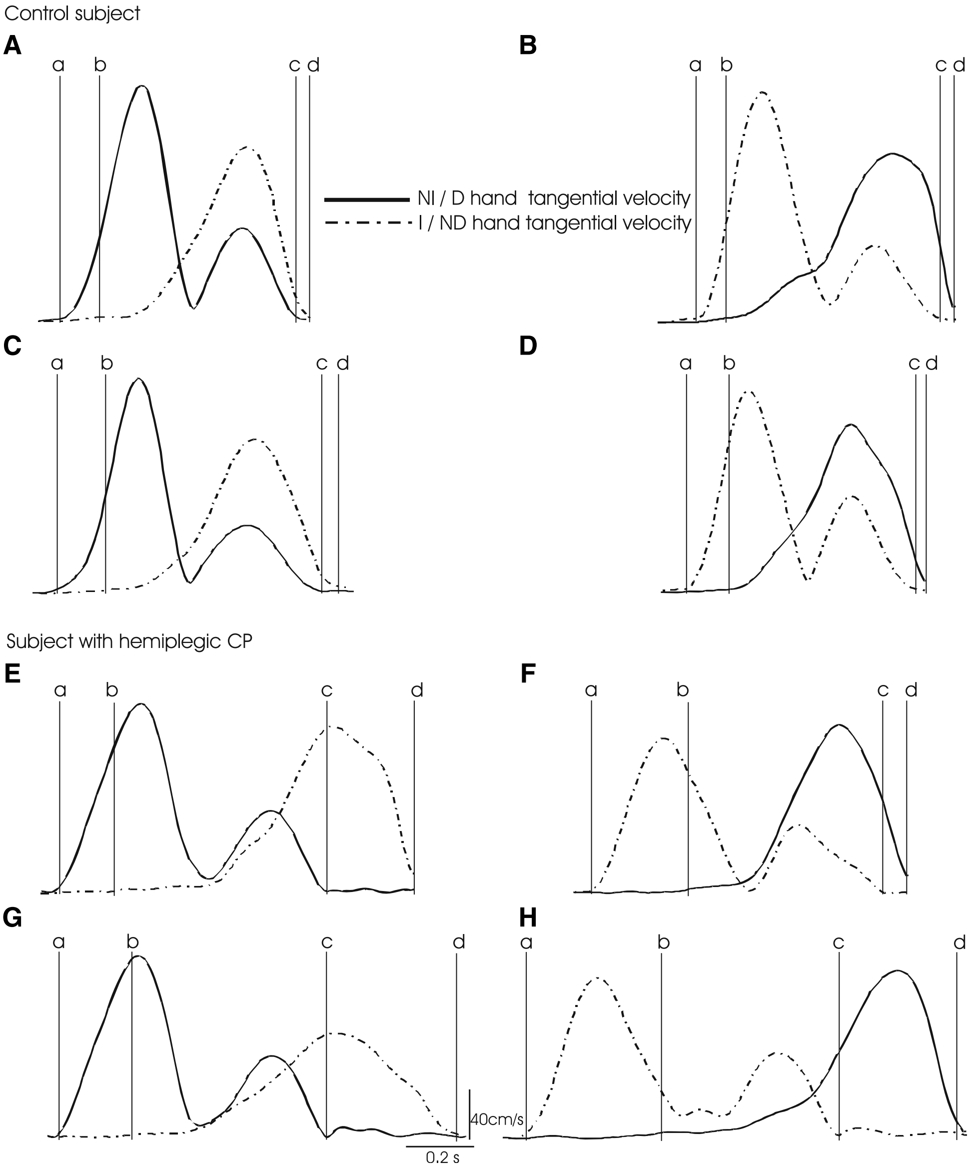

Fig. 2 Tangential velocity kinematic traces of a representative control subject and a subject with hemiplegic CP using the involved (*I*) or non-dominant (*ND*) hand (*solid traces*) or the non-involved (*NI*) or dominant (*D*) hand (*dashed traces*) to open the drawer with a knob handle at a fast-as-possible speed. Control subject using the **A** dominant hand to open the drawer with a large switch inside, **B** non-dominant hand to open the drawer with a large switch inside, **C** dominant hand to open the drawer with a small switch inside, and **D** non-dominant hand to open the drawer with a small switch inside. Child with hemiplegic CP using the **E** non-involved hand to open the drawer with a large switch inside, **F** involved hand to open the drawer with a large switch inside, **G** non-involved hand to open the drawer with a small switch inside, and **H** involved hand to open the drawer with a small switch inside. *a* Movement onset of the drawer hand. *b* Movement onset of the task hand. *c* Movement offset of the drawer hand when the drawer is completely opened. *d* Movement offset of the task hand. *b*, *c* Movement overlap time for the two hands. *c*, *d* Goal synchronization duration. Note that the velocity traces of the task hand terminate above zero if the hand does not decelerate before contacting the switch

Results

Generally, there were clear differences in coordination of the drawer-opening task in the group of children with hemiplegic CP and the control group. Figure 2 shows an example of kinematic traces of the hands for one representative pair of children performing the task with the knob handle and with either the large switch (A, B, E, F) or small switch (C, D, G, H) using non-involved/dominant hand as the drawer hand and the involved/non-dominant hand as the task hand (A, C, E, G) or using involved/non-dominant hand as drawer hand and non-involved/dominant hand as task hand (B, D, F, H). As expected, the child in the control group (Fig. 2A–D) had considerable movement overlap time of the two hands (b, c) and greater goal synchronization (c, d); i.e., a shorter duration between the drawer

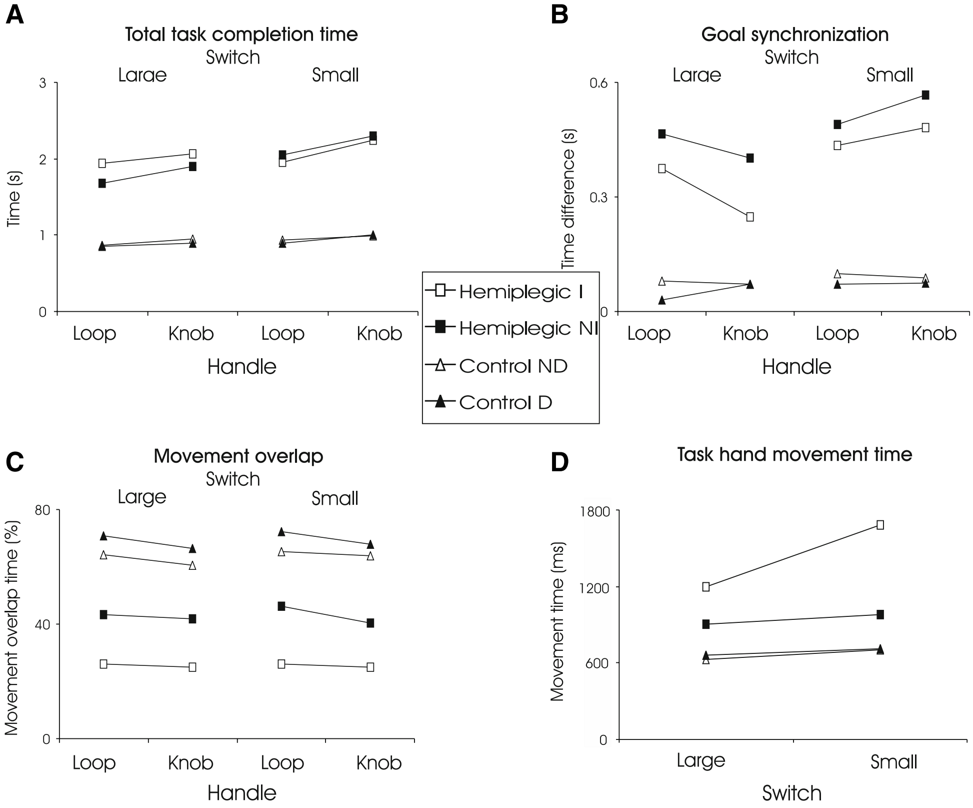

Fig. 3 **A** Total task completion time, **B** average goal synchronization duration (time difference between the two hands completing the task), **C** movement overlap of the two hands normalized as a percentage of total task completion time, and **D** task hand movement time for children with hemiplegia (*square symbols*) and controls (*triangle symbols*) each hand serving as the lead, drawer-opening hand at fast-as-possible speed with two types of handles (loop or knob) and two sizes of switches (large or small). Symbols (see *inset*) refer to the hand used to open the drawer. Note that the data representing the total task completion time and task hand movement time for the control non-dominant hand are obscured by the data representing the control dominant hand

hand completely opening the drawer and the task hand activating the switch. In contrast, the child with hemiplegic CP (Fig. 2E–H) had a longer overall movement time and a more sequential movement, with smaller movement overlap (b, c) and reduced goal synchronization (c, d). For the child in the control group, there seemed to be no effect of the role of each hand (2A vs. 2B, 2C vs. 2D) or additional accuracy constraint (decrease the size of switch from large to small, 2A vs. 2C, 2B vs. 2D) on the movement performance. However, the movement traces of the child with hemiplegic CP differed depending on which hand (involved/non-involved) was the lead hand (2E, vs. 2F, 2G, vs. 2H) and the size of the switch (2E vs. 2G, 2F vs. 2H).

Figure 3 shows the results across all subjects of (A) the total task completion time, (B) goal synchronization, (C) movement overlap, and (D) task hand movement time for the controls (triangle symbols) and the children with hemiplegic CP (square symbols) with each hand serving as the drawer-opening hand for each of the two types of handles and two sizes of switches. Overall, the task completion times of the control group were considerably shorter than for the children with hemiplegic CP for all conditions (main effect of group, $F_{1,20} = 19.82$, $\eta^2 = 0.50$, $P < 0.001$) (Fig. 3A). Additionally, using the knob handle prolonged the completion time for both groups (main effect of handle, $F_{1,20} = 8.32$, $\eta^2 = 0.29$, $P = 0.009$) while decreasing the size of the switch only increased the completion time for the children with hemiplegic CP (group × switch interaction, $F_{1,20} = 7.58$, $\eta^2 = 0.28$, $P = 0.012$, Tukey post hoc $P < 0.05$).

Generally the control group had greater *goal synchronization* of the two hands (shorter delay between opening the drawer and contacting the switch) regardless of the handle, switch, hand conditions (main effect of group, $F_{1,20} = 15.167$, $\eta^2 = 0.43$, $P = 0.001$). Figure 3B shows the goal synchronization results for both groups. For the children with hemiplegic CP, when the involved hand opened the drawer (unfilled square) there was a greater goal synchronization as compared to the non-involved hand (filled square) for all handle and switch conditions (group × hand interaction, $F_{1,20} = 5.55$, $\eta^2 = 0.22$, $P = 0.029$, Tukey post hoc $P < 0.05$). Moreover, the goal synchronization differed significantly when children with hemiplegic CP opened the drawer with the loop or knob handle to activate the two types of switches within the drawer (group × handle × switch interaction, $F_{1,20} = 7.80$, $\eta^2 = 0.25$, $P = 0.011$, Tukey post hoc $P < 0.05$). The effect of the handles differed depending on the size of the switches. With the large switch, changing the handles from the loop to the knob increased goal synchronization. In contrast, changing the handles from the loop to the knob with a small light switch inside the drawer decreased goal synchronization.

Figure 3C illustrates the normalized *movement overlap* time for both groups. The control group had a significantly higher percentage of normalized movement overlap time than the hemiplegic CP group across all conditions (main effect of group, $F_{1,20} = 44.16$, $\eta^2 = 0.69$, $P < 0.001$). The role of each hand only influenced the normalized movement overlap time for the hemiplegic CP group. They demonstrated a higher percentage of movement overlap when the non-involved hand served as the drawer-opening hand (filled) compared to when the involved hand served as the drawer-opening hand (unfilled, group × hand interaction, $F_{1,20} = 5.32$, $\eta^2 = 0.21$, $P = 0.032$, Tukey post hoc $P < 0.05$). However, size of the switches in combination with the type of handle did not affect the normalized movement overlap time for either group.

Children with hemiplegic CP increased the drawer hand movement time from the loop handle (1,218 ms) to the knob handle (1,445 ms) significantly while children in the control group increased slightly (from 789 to 839 ms, group × handle interaction, $F_{1,20} = 10.26$, $\eta^2 = 0.34$, $P = 0.004$, Tukey post hoc $P < 0.05$). When the involved hand used as the drawer hand the movement time increased compared to the non-involved hand for children with hemiplegic CP (group × hand interaction, $F_{1,20} = 7.36$, $\eta^2 = 0.27$, $P = 0.013$, Tukey post hoc $P < 0.05$). Interestingly, the size of the switch affected the task hand movement time significantly only for the involved hand of children with hemiplegic CP (Fig. 3D, group × hand × switch interaction, $F_{1,20} = 10.61$, $\eta^2 = 0.35$, $P = 0.004$, Tukey post hoc $P < 0.05$).

Discussion

The primary purpose of the current study was to evaluate the influences of task constraints on the coordination of asymmetric bimanual control during a functional task in children with and without hemiplegic CP. As hypothesized, the hemiplegic CP group was slower, less coordinated and more influenced by the changes of hand and accuracy constraints on bimanual coordination in this drawer task. Increasing accuracy constraints on the drawer handle (knob handle), but not the switch, seemed to improve bimanual coordination as demonstrated by greater goal synchronization. However, increasing the accuracy demands for both hands (knob handle with small switch) for the children with hemiplegic CP did not result in increased bimanual coordination (i.e., reduced goal synchronization). These findings contribute to a better understanding of bimanual coordination in children with hemiplegic CP, which may aid the development and refinement of more efficacious rehabilitation protocols.

Bimanual coordination in children with hemiplegic CP

Bimanual coordination was impaired in the hemiplegic CP group compared to the control group, who demonstrated large movement overlap and greater goal synchronization of the two hands. As discussed in our prior study (Hung et al. 2004), the nature of the current functional task requiring asymmetrical movements of the two hands differed from tasks used in other studies (Sugden and Utley 1995; Steenbergen et al. 1996, 2000, 2008; Utley and Sugden 1998; Utley et al. 2004). This may account for divergent findings in regard to temporal coupling of the two hands during the bimanual tasks. Tasks in these studies involved simple symmetrical (homologous) movements of the two hands. The non-involved hand slowed down and mimicked the movement of the involved hand, and as a result, the two hands achieved their goal with minimal time discrepancy. In the current study, coordination of this functional, asymmetric task could not be compensated for by slowing down the non-involved hand to maintain good bimanual coordination. Rather, in the previous asymmetric bimanual drawer study, children with hemiplegic CP were found to speed up the non-involved hand to activate the switch (Hung et al. 2004). Thus, the findings seemingly depend on task constraints.

Accuracy constraints

Several studies have indicated that increasing accuracy constraints or making a task more complex may precipitate the uncoupling of the two hand movements during bimanual activities for children with hemiplegic CP (Utley and Sugden 1998; Steenbergen et al. 1996; Gordon and Steenbergen 2008). In the current study, this occurred only when increased accuracy constraints were imposed on both the drawer and task hands. Goal synchronization was reduced when the smaller switch was used in combination with the knob handle (higher accuracy demand). In contrast, the use of the knob handle with the larger switch (high and low accuracy constraints, respectively) facilitated better goal synchronization. Therefore, accuracy constraints should be manipulated carefully to facilitate better bimanual coordination by not overloading the complexity of the task. Interestingly, Utley et al. (2004) also found that the accuracy demand of their symmetric bilateral reaching and grasping task facilitated better bimanual coupling. Thus, the differential results of these studies suggest that the effect of accuracy constraints on bimanual coordination is task-dependent.

Utley and Steenbergen (2006) hypothesized two interactive control processes for bimanual tasks: a common control process that controls and coordinates both hands as one unit and a hand-specific control process that controls individual hand movement. Since weight given to common and hand-specific control processes were proposed to vary according to the task constraints, tasks that activate more of the common control process would increase the bimanual coordination. For the common control process, distinct motor cortex regions activated during ipsilateral or bimanual hand movements might be responsible (Aizawa et al. 1990; Kim et al. 1993; Cramer et al. 1999; Verstynen et al. 2005). Recently, in a functional magnetic resonance imaging study, Aramaki et al. (2006) found reduced contralateral innervation of the non-dominant motor cortex and a stronger involvement of the ipsilateral dominant motor cortex during a bimanual task. They suggested that the decreased activity of the non-dominant motor cortex could enhance neural crosstalk. Verstynen et al. (2005) further indicated that strong ipsilateral activity in the dominant motor cortex was specific to complex movements which required more movement components. The knob handle used in the current study requires more precise lateral pinch of the thumb than the loop handle (which only requires a hooking movement). Therefore, the knob handle (higher task constraints) might facilitate more a common control process and improve bimanual coordination.

The two different types of accuracy constraints affected the hand movement time for children with hemiplegic CP. The drawer hand movement time was longer for the knob handle than the loop handle for both involved and non-involved hands while the task hand movement time was longer for the smaller switch only for the involved hand. The knob handle which required a more complex movement control seemed to had a general impact for children with hemiplegic CP and thus affected the bimanual coordination. On the other hand, altering the switch size changed the accuracy constraints but not the complexity of the tasks, and resulted in a longer movement time for the involved hand only. This is in agreement with findings suggesting that movements of children with hemiplegic CP are affected by accuracy constraints despite their movement limitations (Smits-Engelsman et al. 2007; Gordon et al. 2003). As predicted, the two different types of accuracy constraints did not affect the drawer hand or the task hand movement time for the control group.

Interestingly, the movement overlap time was not influenced by the various accuracy constraints even though this did influence the goal synchronization. In other words, the time in which both hands were moving relative to the total movement time during the task remained stable while the ending time for each hand changed. This finding might be the result of compensatory strategies of the hands.

Although speed was found to facilitate bimanual coordination for both symmetric and asymmetric tasks (Utley and Sugden 1998; Hung et al. 2004), prolonged total movement time (slower speed) while increasing accuracy constraints to either the handle or the switch for the hemiplegic CP group did not cause a general decrease in the bimanual coupling. Therefore, movement completion time is not the sole indication of the quality of bimanual coordination. Direct examination of the bimanual coordination pattern is necessary during this task. A limitation of the present study is that the considerable differences in movement time between the two groups could affect our findings. A study that controls the movement time of the two groups may help address this limitation.

Conclusions

Children with hemiplegic CP showed reduced bimanual coordination compared to typically developing children in this asymmetric drawer task. Their performances were influenced by the roles of the involved and non-involved hand, and the accuracy demands. Therapists should be aware that changing the role of each hand during bimanual tasks and manipulating accuracy constraints of the tasks are important so children with hemiplegic CP can learn to adjust their bimanual coordination according to the various task constraints in their daily environment. Importantly, performance may not be linearly related to the constraints, and in some cases "more is not better." Recently, structured practice with the involved and non-involved hands forms the basis for such intervention strategies as bimanual training (Charles and Gordon 2006), whereby the involved hand is engaged in extensive bimanual practice (Gordon et al. 2007, 2008). Further knowledge about how the two hands interact and are affected by task and accuracy constraints may help to further refine such rehabilitation strategies.

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