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Influence of Task on Interlimb Coordination in Adults with Cerebral Palsy

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Abstract

Objective—To examine movement time and kinematic properties of unilateral and bilateral reaching movements in adults with cerebral palsy (CP), focusing on how different types of bilateral movements, simultaneous or sequential, may influence interlimb coordination.

Design—Quantitative study using between group repeated measures analyses.

Setting—motor control laboratory at a research university.

Participants—Adults with hemiplegic CP ($n=11$; mean age 33 ± 10 y, 4 males) and age matched controls (mean age 32 ± 9 y, 4 males).

Interventions—Not applicable.

Main Outcome Measures—Movement time (MT), maximum deviation from a straight trajectory to the target, and peak speed.

Results—Although adults with hemiplegic CP demonstrated strong unilateral deficits, bilateral simultaneous reaching movements were temporally and spatially coupled. Movement of the less affected arm slowed to match the movement of the more affected arm. In contrast, bilateral sequential movements improved MTs of the less affected and more affected arms.

Conclusions—Bilateral sequential movements were conducive to faster MT compared to unilateral or bilateral simultaneous movements. Training that includes bilateral sequential movements may be beneficial to adults with hemiplegic CP. Upper limb movements are coordinated in a variety of ways to perform routine bilateral tasks. Some bilateral tasks require more symmetrical movements of the upper limbs such as stacking boxes. Other bilateral tasks emphasize coordinated sequential action between upper limbs such as opening the refrigerator with one hand while placing an item on the shelf with the other hand. Despite the prevalence of

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integrative upper limb use, the control of different forms of bilateral movement is not well understood. A more comprehensive knowledge of upper limb bilateral movements may hold important implications for developing more effective upper limb movement therapies.

Keywords

Cerebral palsy; Adult; Movement; Rehabilitation; Upper extremity

In healthy adults bilateral simultaneous upper limb activities are characterized by spatiotemporal coupling. A classic study by Kelso et al¹ in which bilateral simultaneous (bilat sim) reaches made to targets at different distances had similar movement times, was the first to suggest temporal coupling between upper limbs. Since then several other studies have confirmed findings of temporal coupling.²⁻⁴ Spatial coupling has also been noted. Attempts to simultaneously draw two different shapes result in hybrid drawings of the two shapes.^{5, 6} Spatial and temporal coupling may be a way for the central nervous system to diminish control requirements,^{1, 7} a concept that has the potential to be useful in rehabilitation.⁸

The interdependence of movement parameters in simultaneous bilateral movements may present an effective rehabilitation option for hemiplegia. There is evidence of enhanced performance of the more affected upper limb in bilat sim compared to unilateral movements following stroke.^{9, 10} This includes shorter MT,¹⁰ and faster peak velocities^{9, 11} in bilat sim tasks. Unlike adults with hemiplegia due to stroke, children with hemiplegic CP do not demonstrate an improvement in MT of the more affected arm in bilat sim movements.¹²⁻¹⁴ In fact, in children with hemiplegic CP, both less affected and more affected arm performance on a bilateral tapping task tended to degrade.¹³ Differences in outcomes between studies involving individuals with CP and those with stroke may be related to lesion site as participants in these studies may likely have variation in the regions affected. In a radiological study of children with hemiplegic CP, bilateral lesions were commonly noted,¹⁵ whereas focal unilateral lesions are widely associated with hemiplegia in adults with stroke.¹⁶⁻¹⁸ While both groups present with hemiplegia, lesion characteristics have been associated with functional outcome¹⁹ and therefore, may influence movement performance in each group. Another plausible explanation for the performance differences noted between groups with stroke and CP may have roots in developmental theory. Life experiences coordinating upper limbs may contribute to performance differences between the two groups. Adults with stroke have had the experience of typical function in both upper extremities whereas individuals with CP have grown up with limitations in upper limb function.

Our understanding of motor performance in CP is based on research focusing on children. Less is known, however, about the characteristics of upper limb movement in adults with CP. It is unclear if adults with CP would display characteristics similar to children with CP; thereby suggesting that onset of hemiplegia plays a critical role in performance. Alternatively, adults with CP may display characteristics similar to adults with stroke suggesting that the developmental process allows for improved movement of the more affected hand in bilateral simultaneous tasks.

Our aim was to investigate differences in unilateral and bilateral reaching movements in adults with CP. Specifically, we examined if adults with CP demonstrated improved performance of the more affected arm during bilateral movements. In addition to exploring the traditional paradigm of bilat sim movements, we included bilateral sequential (bilat seq) movements. Expanding our investigation of bilateral movements to include bilat seq movements may provide greater insight into interlimb coordination as underlying neural mechanisms may not be identical for the two forms of bilateral movement.²⁰ We hypothesized that adults with CP would demonstrate coupled movement in the bilateral simultaneous task with the less affected hand slowing to match the more affected hand, similar to children with CP.¹³ As bilat seq movements have not been well studied, characterizing these movements in adults with CP. While bilat sim movements have been widely investigated in healthy controls and individuals with motor impairments, much less is known about the control of bilateral movements produced sequentially. Thus, we included both bilat sim and sequential tasks. A simple reaching paradigm was chosen to examine differences in bilateral movements in adults with CP. Currently, there is little information available on motor performance of adults with CP. The results of this study will start to address this gap and may be a spring board for future studies addressing aging with a disability. An age matched control group was included to better understand differences between typically developing participants and participants with CP in adulthood.

Methods

Participants

Eleven adults (mean age 33 ± 10 y, 4 males) with hemiplegic CP (7 right more affected, 4 left more affected) and ten controls (mean age 32 ± 9 y, 4 males) participated in the study. All were independent community dwellers reporting a marked reduction in the ability to use the more affected upper limb in activities of daily living. The Motor Activity Log²¹ (MAL) which measures self reported amount of use and quality of movement for the more affected arm was used to assess upper limb use in daily activities. The Gross Motor Function Classification System²² (GMFCS) was used to assess motor disability. Demographics for the group with CP are reported in Table 1. At the time of testing, none of the participants were receiving medical treatment, including rehabilitative services related to upper limb function. All participants provided informed consent following the guidelines established by the University of Michigan Institutional Review Board and were financially compensated for their time.

Experiment Procedures

Participants were seated in a chair with back support in front of a table with a target board attached to it. Participants performed unilateral bilat sim and bilat seq reaching movements to the target board always starting from and returning to the marked home position. The home position was standardized by having participants place their hands in a pronated position at the edge of the table, shoulder width apart with their elbows flexed 90 degrees. The home position was marked with a 7.5 cm piece of red tape. Targets were positioned on the board directly in front of each shoulder. Distance to the target was held constant by measuring the participant's reach distance with his/her shoulder flexed to 90 degrees and

placing the target at 80% of this distance. Participants were instructed to move as quickly as possible to the target and back to home position upon hearing the verbal “go” signal. It was emphasized that participants should reach forward with their arm rather than lean forward with their trunk. Movements were monitored and trials were repeated if there was notable trunk movement. During unilateral and bilat sim conditions, five consecutive cycles of reaching to the target and returning to home position were performed by each arm. In the unilateral condition each upper limb moved separately and in the bilat sim both upper limbs moved together. For the bilat seq condition, participants first reached to the target and returned to the home position with the less affected upper limb followed immediately by a movement of the more affected upper limb to the target and back to home position. Three reaches were made with each upper limb for this task for a total of six consecutive reaches. The total number of reaches in the bilat seq task was limited to six in order to keep the overall time necessary to complete each of the three tasks relatively comparable. The order the tasks were introduced was always the same: unilateral, bilat sim, and bilat seq. Prior to starting each task the participants were allowed to clarify the directions for that task. All adults with CP had complete data sets for this study. Two individuals in the control group were missing one or two data points in the unilateral condition.

Data Acquisition and Analysis

Data were collected using the Motion Monitor version 8 system^a, which uses a 3D electromagnetic field to capture movements at a sampling rate of 100 Hz. Sensors^a were attached directly to the dorsal surface of the hand using medical grade tape. In addition, prewrap was used to further secure the sensors and cables along the length of the arm. Sensors were used to record the trajectory during reaching movements. Following testing, data were exported, filtered using a fourth order Butterworth low pass filter with a 5Hz cutoff, and analyzed using custom Matlab^b software. The start and stop of each movement were identified using interactive software. The movement aspects of interest were total movement time (MT), peak speed and maximum deviation. All outcome measurements were based on the complete movement from the home position to the target and back to the home position. The amount of time between the hand leaving and returning to the home position determined MT. Sensor displacement data were used to calculate instantaneous speed. A resultant speed was calculated from the x, y and z components. To determine maximum deviation, a straight path from the home position to the target was calculated. The point in the trajectory farthest away from the derived line was identified and the distance between the derived line and point were determined.^{23, 24}

Statistical Analyses

A repeated measures analysis of variance was used to analyze the relationship between group (CP or control), task (unilateral, bilat sim, or bilat seq), and limb (more affected or less affected) including all two and three way interactions. The analysis was carried out using the Mixed procedure in SPSS. This procedure was better suited to this data set than the traditional General Linear Model approach, as this statistical method can accommodate the unbalanced data set caused by a slight reduction in number of trials during the bilat seq task. Pair wise comparisons using Sidak adjustments for multiple comparisons were used to carry out post-hoc tests for interactions that were statistically significant ($\alpha=.05$).

Results

Overall, the adults with CP demonstrated longer MT (main effect, $F_{(1, 19.018)}=19.145$, $p<.01$) greater deviation (main effect, $F_{(1, 19.207)}=26.677$, $p<.01$) and lower peak velocities (main effect, $F_{(1, 19.006)}=5.661$, $p=.03$) than the control group. Figure 1 depicts movement patterns for each group. Our primary hypothesis was that adults with CP would demonstrate coupled movement in the bilat sim task. More specifically, the less affected hand would slow to match the more affected hand, similar to the performance of children with CP¹³. We also explored bilat seq movements as this type of bilateral coordination is rarely investigated yet it reflects common motor behavior in routine activities.

Movement Time

While the control group demonstrated similar MT with both hands on all tasks (Figure 2A), adults with hemiplegic CP altered their MT based on the task performed and the hand used (Figure 2B, group $\times$ task $\times$ hand interaction: $F_{(2, 512.999)}=8.269$, $p<.01$). In unilateral movements, the more affected hand had longer MTs compared to the less affected hand ($t=8.89$, $p<.01$). When the two arms were moving at the same time in the bilat sim task, the less affected MT slowed resulting in MT of the less affected and more affected arms that were equivocal ($t=1.05$, $p=.29$). This is similar to previous work involving children with CP.¹³ Interestingly, in the bilat seq task, in which the participant was required to coordinate successive movements of the less affected and more affected arms, MT of both arms were reduced compared to the unilateral task (less affected: $t=4.17$, $p<.01$; more affected $t=3.25$, $p<.01$). Thus, sequencing movements of both upper limbs resulted in shorter MT for each limb compared to repetitive movements of the same limb. This demonstrates that bilat seq movements are not simply the sum of two unilateral movements and that bilat seq movements have a positive effect on MT in adults with CP.

Maximum Deviation

Changes in quality of movement as measured by the maximum deviation from the straightest path to the target also showed a group by task by hand interaction ($F_{(2, 512.021)}=3.84$, $p=.02$). The control group demonstrated greater deviation with the non dominant arm compared to the dominant arm in the unilateral task (Figure 2C, $t=1.98$, $p=.05$). The adults with CP, demonstrated greater deviation with the more affected limb compared to the less affected limb in both the unilateral (Figure 2D, $t=5.53$, $p<.01$) and bilat seq ($t=1.91$, $p=.05$). However, in the bilat sim task, the hand path deviation of the less affected limb increased compared to both the unilateral task ($t=8.08$, $p<.01$) and the bilat seq task ($t=6.23$, $p<.01$). Likewise, the more affected arm also demonstrated increased deviation in the bilat sim task compared to both the unilateral ($t=2.40$, $p=.05$) and bilat seq ($t=2.86$, $p=.01$) tasks. The maximum deviation in the bilat sim task was equivocal for the less affected and more affected arms ($t=1.09$, $p=.27$). There was no significant difference in the amount of deviation between the unilateral task and the bilat seq task for either arm (less affected $t=1.87$, $p=.17$, more affected $t=.78$, $p=.82$). This underscores that the form of bilateral task influences performance.

Peak Speed

Peak speed for each arm was similar in the control group (Figure 2E) whereas the adults with CP demonstrated a greater peak speed with the less affected arm (Figure 2F, group $\times$ arm interaction $F_{(2, 511.992)}=12.71$ $p<.01$). Surprisingly, the control group showed differences in peak speed between tasks with a slower peak speed in the bilat seq task compared to the unilateral and bilat sim tasks. The adults with CP had similar peak speeds for all tasks (group $\times$ task $F_{(2, 511.992)}=17.57$ $p<.01$). Overall, bilat sim tasks resulted in changes in MT and maximum deviation for adults with CP, but peak speed was unaffected. It is important to note that not all kinematic measurements worsen in a bilat sim task in adults with CP.

Discussion

Predictably, our results demonstrated that adults with hemiplegic CP have slower movement times compared to aged matched peers. In agreement with our primary hypothesis, adults with CP demonstrated a temporal and spatial coupling in the bilat sim task where the less affected arm slowed and showed greater handpath deviation. An examination of bilat seq movements provided interesting results. When the upper limbs were coordinated in a bilat seq task, both MT and maximum deviation improved compared to the bilat sim task. Furthermore, MT in the bilat seq task was faster than MT in the unilateral task for both the more affected and less affected arms. Our findings show that bilat seq tasks have a positive effect on MT in adults with CP. These results emphasize the need to consider what form of bilateral activity is best suited to the clientele in upper limb rehabilitation programs. Previous literature has promoted the use of moving both arms simultaneously to facilitate performance in adults with stroke,^{9-11, 25, 26} little attention has been given to other forms of bilateral activities such as moving the arms sequentially.

Life experiences requiring coordination of the upper limbs may contribute to the facilitative effect that bilat seq activities may have for adults with CP. Individuals with hemiplegic CP start their lives with lateralized movement deficits that may complicate the performance of coordinated bilateral upper limb movements. In a study including children with CP and typically developing children, there was a notable difference in the performance of a bilateral task involving simultaneous opening of a drawer with one hand while reaching into the drawer to touch a switch with the other hand. Typically developing children demonstrated more simultaneous movements of both hands while children with CP performed the task in a more sequential fashion by pulling the drawer open and then reaching in to touch the switch.²⁷ This tendency to perform more sequential movements in childhood may impact performance of bilat seq movements as an adult and may help explain diminished performance in the bilat sim task.

Intriguingly, MT in the bilat seq task was faster than MT in the unilateral task. It should also be noted that handpath accuracy was not compromised as a result of increased MT in the bilat seq task. In both the unilateral and bilat seq tasks participants were instructed to make repetitive movements. In the unilateral task, participants made five consecutive movements with either the less affected or more affected upper limb. In the bilat seq task, the two arms were moved reciprocally. As previously stated, a defining difference in these two tasks is the

use of two rather than one arm to make consecutive movements. Our findings of more efficient movement in the bilat seq task parallels previous research demonstrating movement benefits when two limbs, either upper or lower, were involved. For example, movement sequences using two effectors (hands or feet) resulted in decreased variability of movement compared to movement sequences in a single effector.²⁸ As this form of bilateral movement has not received the same degree of attention as bilat sim movements, further research is necessary to more fully understand how the central nervous system controls bilat seq movements and if they may be a useful adjunct in movement therapies.

Research has focused on training programs that emphasize bilateral arm training with synchronous movements^{9, 29-31} or unilateral training programs.³²⁻³⁴ Both of these training programs have resulted in improved movements following the intervention. Since it is unlikely that any one treatment approach addresses all aspects of upper limb mobility, it is important to continue to develop interventions that target various components of movement. Our results suggest that bilateral sequential movements may serve a valuable role in training protocols. A telerehabilitation program which incorporated both bilat sim and seq activities has successfully demonstrated improved performance in adults with CP, including an improvement in MT.³⁵ These results are promising and encourage more specific testing of bilateral activities in rehabilitation.

Other factors may have also contributed to our outcomes. Performance in unilateral, bilat sim and bilat seq tasks may be related to the ability to appropriately recruit brain regions that contribute to each task. While many of the same brain regions contribute to both unilateral and bilat movements, such as the sensorimotor cortex and supplementary motor area, the amount of activation differs in unilateral versus bilateral tasks^{30, 36, 37} and in bilat sim versus bilat seq tasks.²⁰ It is possible that adults with CP may more efficiently recruit the appropriate amount of activation for bilat seq tasks. Similar to behavioral studies, imaging studies rarely include bilat seq tasks, therefore little is understood about this type of bilateral coordination.

Another factor that may have influenced performance was the use of two targets in the bilat sim task. Participants were required to split their attention between the two targets as they reached. However, if divided attention played a key role in the bilat sim task we would have expected performance of both the more affected and less affected arms to diminish. However, diminished performance was only noted in the less affected arm. Thus, dual targets do not appear to have been a contributing factor to MTs in the bilat sim task.

This research contributes to the field of rehabilitation by providing information on an understudied group, adults with CP. Comparing our results with previous literature involving adults with stroke; it seems that bilat sim activities are advantageous to the performance of the more affected arm following stroke⁹, but not CP.¹³ A limitation of this study is that we have not directly compared these two groups. Future studies should address this issue to help tease out the influence of motor development in adults with hemiplegia.

Conclusion

In adults with CP, bilat sim tasks did not enhance performance of either upper limb. This parallels findings in children with CP¹³ and contrasts findings in adults with stroke.⁹ It is possible that developmental history may influence interlimb coordination in adults with hemiplegia. Interestingly, bilat seq tasks had a facilitative effect on MT for both upper limbs in adults with CP. This emphasizes the need to expand research of bilateral movements to include the many forms of bilateral upper limb coordination.

Suppliers

- a. Motion Monitor version 8 (http://www.ascension-tech.com/docs/Flock_of_Birds.pdf) and Sensors (<http://www.ascension-tech.com/realtime/RTMotionSTARTethered.php>); Ascension Technology Corp, 107 Catamount Dr, Milton VT 05468-3284.
- b. The MathWorks, 3 Apple Hill Dr, Natick, MA 01760-2098.

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List of Abbreviations

CP	cerebral palsy
MT	movement time

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Figure 1.

Sample raw data traces of A.) movement of the dominant hand of a control participant, B.) movement of the less affected hand of a participant with stroke, C.) movement of the more affected hand of a participant with stroke. Arrows indicate direction of reaching movement (upward arrow – reach movement, downward arrow – return movement). Abbreviations: LA, less affected; MA, more affected.

Figure 2.

Kinematic analyses: A.) Movement time in control group (Mean +1 SE), B.) Movement time in adults with CP. (Mean +1 SE), C.) Maximum deviation in control group (Mean +1 SE), D.) Maximum deviation in adults with CP (Mean +1 SE), E.) Peak speed in control group (Mean +1 SE), F.) Peak speed in adults with CP (Mean +1 SE).

Table 1

Demographic data for participants with CP. The Motor Activity Log is based on a 0-5 scale, 0 demarks that the more affected arm is not used and 5 indicates that the more affected arm functions similar to the less affected arm. Gross Motor Function Classification System (GMFCS, levels I-V). Level I represents the ability to walk indoors and outdoors, and climb stairs without limitations. Level 5 indicates that all areas of motor function are limited and that adaptive equipment and/or assistive technology cannot fully compensate for functional limitations.

Participant	Age	Affected Side	Motor Activity Log Amount of Use	Motor Activity Log Quality of Motion	GMFCS
1	40.8	left	2.62	3.38	II
2	24.7	right	2.99	3.58	I
3	36.8	right	0.75	0.75	I
4	35.1	right	1.11	0.82	I
5	34.2	left	0.96	1.05	I
6	38.0	left	0.68	0.68	II
7	21.9	right	0.86	0.64	I
8	22.8	right	1.71	1.93	I
9	20.7	left	1.25	1.21	I
10	57.2	right	1.64	1.61	III
11	32.5	right	0.5	0.39	I