Shoulder and Hand Displacements During Hitting, Reaching, and Grasping Movements in Hemiparetic Cerebral Palsy

Edwin Van Thiel and Bert Steenbergen

In this study, we examined the degree and timing of shoulder displacements during hitting, reaching, and grasping movements performed by young adults with hemiparetic cerebral palsy. The participants performed unimanual and bimanual arm movements towards targets and objects of different sizes. On the basis of the assumption that shoulder displacement due to trunk translation and rotation is a successful, adaptive reaction to reduced joint mobility in the affected arm, the fluency of hand displacements was expected to remain invariant under variations of shoulder displacement as is also the case in healthy participants. The results point in this direction. With respect to the timing of shoulder displacement, prior research suggested that hemiparetic movements can be characterized by inconsistent motion-timing patterns—that is, the timing of shoulder and hand-displacement onsets varied between trials. Therefore, the within-subject variability of the movement-onset asynchrony between hand and ipsilateral shoulder displacement was expected to be larger on the impaired side than on the unimpaired side. This prediction was not confirmed, which challenges these earlier conclusions. Additionally, we also examined the peak-velocity asynchrony of the hand and shoulder. Contrary to the onset asynchrony, the peak asynchrony varied between the hitting and reaching task and between the hitting and grasping task. For the reaching and grasping tasks, there were also significant differences between hands. Again, variability of the (peak-velocity) asynchrony was not significantly increased when comparing the impaired hand with the unimpaired hand. The results suggests that the hemiparetic participants were capable of flexibly recruiting and sequencing the various degrees of freedom of their impaired side required for successful task completion, albeit in different magnitudes and sequenced differently.

Key Words: hemiparesis, cerebral palsy, degrees of freedom, asynchrony, recruitment

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Introduction

Unrestricted arm movements in healthy humans are generally accompanied by movements of the trunk either to maintain balance or to contribute to successful task completion. Furthermore, task constraints influence the degree to which the trunk is moved during task performance (e.g., in pointing: Ma & Feldman, 1995; Kaminski et al., 1995; in grasping: Steenbergen et al., 1995; Saling et al., 1996; Marteniuk & Bertram, this issue; in eating: Van der Kamp & Steenbergen, 1999). Despite the fact that a variety of task constraints were varied in the just mentioned studies, a common finding was the absence of an effect of variations in shoulder displacement on end-effector kinematics or fluency (e.g., Kaminski et al., 1995; Ma & Feldman, 1995; Marteniuk & Bertram, this issue). In addition, displacement of the shoulder due to trunk translation and rotation was shown to consistently precede end-effector displacement, suggesting an invariant and stable timing pattern of the successive involvement of proximal and distal parts of the effector system (e.g., Ma & Feldman, 1995, and to a lesser degree, Saling et al., 1996).

The flexibility in healthy participants to recruit different effectors to achieve the same movement outcome is most likely due to the availability of the vast repertoire of degrees of freedom they have at their disposal (Bernstein, 1967). In participants with cerebral palsy, however, the movement repertoire has been drastically reduced from an early age on. The unilateral nature of the deficits associated with hemiparetic cerebral palsy allows a comparison between the recruitment of multiple degrees of freedom on the affected and non-affected side and thereby the study of the incorporation of degrees of freedom in purposeful acts in general. In the present study, we therefore examined the degree and timing of hand and shoulder displacements in participants with hemiparetic cerebral palsy.

To date, the degree and timing of shoulder displacements in movements performed by people with cerebral palsy have only been studied in isolated movement tasks. In the present study, however, we address this issue in three different motor tasks: hitting, reaching, and grasping. The main objective of our study was to gain more insight into the role of shoulder displacements in movements performed by people with hemiparetic cerebral palsy. In addition, the study also allowed us to establish the generality of some of the conclusions reported in related studies to which we turn next.

Several studies have addressed the issue of the timing of shoulder displacement in motor tasks performed by hemiparetic patients. For example, with respect to pointing movements in hemiparetic patients, Archambault et al. (1999) and Cristea and Levin (2000) examined whether the timing pattern of shoulders and endpoint motion was disrupted. In the Archambault et al. (1999) study, participants were required to reach for a target (a) without shoulder motion, (b) with forward shoulder motion (in-phase movements), or (c) with backward shoulder motion (out-of-phase movements). Although the patients were able to compensate for the effects which the various degrees of shoulder involvement had on the displacements of the hand, they accomplished this at the cost of a reduced movement fluency as reflected by a larger number of zero crossings in the acceleration profile compared to healthy participants. Additionally, Archambault et al. (1999) found an inconsistent sequencing in the recruitment of the shoulders and hand in stroke patients—that is, the timing of shoulder and hand onsets was found to vary considerably between trials. They suggested that the recruitment and sequencing of different degrees of freedom may be impaired in hemiparetic participants.
Cristea and Levin (2000) correlated deficits in hemiparetic patients both with the level of functional impairment and with the size of shoulder displacements. Additionally, to examine the effects of having to rely on proprioceptive feedback only, participants in their study were asked to make pointing movements without visual feedback. It was shown that the use of compensatory strategies was indeed related to the degree of motor impairm…
Method

Participants

A group of 8 mild to moderate hemiparetic individuals were selected to participate in the experiments. Six participants took part in both the reaching and grasping experiment, and 7 participated in the hitting experiment. Only 5 participants performed all three tasks because not all participants were capable of either holding the rod in the hitting task or grasp the objects in the grasping task. At the time of the experiments, the participants were pupils at the Foundation Werkensrode, where they followed an adapted educational program. Additional participant information is given in Table 1.

Task

Figure 1a shows the experimental setup for the hitting task. In this task, participants performed unimanual and bimanual hitting movements with hand-held rods to circular targets projected on a screen. Targets were projected on the screen by means of a beamer, either in front of the impaired arm, in front of the unimpaired arm, or in case of two equally sized targets, one in front of each arm. The participant had to hit a single target with the corresponding arm or, when both targets were presented, to hit these with both arms simultaneously. Participants were instructed to hit the target(s) with the tip of the rod quickly, immediately after target appearance. A similar setup was used in the reaching and grasping experiments, but now participants had to either push a button or grasp and lift small blocks. The experimental setup for the reaching task is shown in Figure 1b. The participant sat at a table and rested his/her hand on start boxes. The illumination of LEDs embedded into the table just in front of the button to be pushed, or block to be grasped, indicated both start and type of trial. When only one LED was illuminated, the participant had to perform the task with the corresponding arm. When both LEDs

<table>
<thead>
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<th>Participant</th>
<th>Tasks performed</th>
<th>Age</th>
<th>Diagnosis</th>
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<td>19</td>
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<td>RP</td>
<td>H</td>
<td>17</td>
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Note: All participants were male. H: hitting; R: reaching; G: grasping.
Figure 1 — Top views of the hitting task (a) and reaching task (b). In the hitting task, the participant held a rod (21 cm: diameter 2.5 cm) in each hand. Attached to the tip of the rod was the pod of a badminton shuttlecock to enable firm but safe impacts with the screen. The rod was made from light wood and was covered with duct tape to realize a comfortable grip. For a comprehensive description of the materials used and procedures applied in the reaching and grasping task, see Steenbergen et al. (2000).
were illuminated the participant had to perform the task bimanually. Participants were instructed to perform the task as quickly as possible upon illumination of the LEDs. The grasping task was identical to the reaching task with the exception that small blocks had to be grasped and lifted. In all three tasks, two target sizes that were tested in separate blocks were used. In the hitting task targets with a diameter of 2 cm (small) and 5 cm (large) were used. In the reaching and grasping task, buttons of 3 cm and 5 cm in diameter and blocks with a width of 3 cm and 5 cm were used. Twelve replications of each condition had to be performed, resulting in 72 trials per task per participant.

Measurement and Data Analysis

In the reaching and grasping task IREDs (Infra-Red light Emitting Diodes) were placed on the wrists and shoulders of both arms of which the displacements in time were recorded at 200 Hz by means of a 3D motion tracking device (Optotrac 3020). The placement of the IREDs is shown in Figure 1b. For the hitting task, the placement of the shoulder IREDs was the same as in the reaching and grasping task, and the displacement of the tip of the rod was calculated from three IREDs attached to the end of the rod (see Figure 1a). The displacements of the wrist in the reaching and grasping task and the displacements of the tip of the rod in the hitting task were both treated as hand displacements.

Several kinematic variables were computed from the displacement measurements after filtering with a second order Butterworth filter with zero-phase lag and an effective cut-off frequency of 20 Hz. Movement time was defined as the time between start and end of movement. Start of the movement was determined by finding the moment prior to the moment of peak tangential velocity at which the hand reached 10% of the peak velocity. The same procedure was applied to the shoulder displacement to determine the start and the moment of peak velocity. Whereas, start of displacement and moment of peak velocity could be determined by automatic segmentation using custom written software for both the hand and shoulder, the end of hand and shoulder displacements was determined by semi-interactive segmentation. The end of the movement was defined as the moment at which the hand reached the target. Note that we thereby excluded the grasping phase (i.e., finger-object manipulation) of the grasping task. This procedure allowed comparisons between tasks as we determined the same moments for all three tasks; the start of movement, moment of peak velocity, and moment of contact with either the screen, button, or block. Trials with excessive movement times, excessive late starting moments, or otherwise erroneous task execution were marked invalid and were excluded from the analyses.

Shoulder involvement was defined as the absolute Euclidean distance traveled by the shoulder from the start to the end of movement. A measure of dysfluency of the hand movements was calculated as the number of peaks and valleys in the tangential velocity profile of the hand between the start and end of the hand movement. Since these values covary with movement time, they were time-normalized to be able to compare them across tasks and across arms.

Two measures reflecting the timing of the shoulder displacement relative to the hand displacement were calculated. First, by subtracting the time at which the hand started to move from the time at which the (ipsilateral) shoulder started to move, we obtained a measure of onset asynchrony. Secondly, by applying the same
procedure to the moments of peak velocity for the hand and shoulder, we obtained a measure of peak-velocity asynchrony. Both measures were considered indices of the sequencing of segment involvement. Therefore, in the remainder of this article, we will use the term sequencing for these asynchrony measurements. For both these measures, the standard deviation over trials served as a measure of the within-subject variability of sequencing.

**Design and Statistical Analyses**

For each task separately (hitting, \( n = 7 \); reaching, \( n = 6 \); grasping, \( n = 6 \)), we analyzed statistically the effects of task execution (unimanual, bimanual), hand (impaired, unimpaired), and target size (large, small) on six dependent variables: (a) distance traveled by the shoulder, (b) dysfluency of the hand movement, (c) onset sequencing, (d) variability of onset sequencing, (e) peak sequencing, and (f) variability of peak sequencing. Only within-task effects were analyzed statistically using a three-within subject factors repeated measurement design. Between-task comparisons of means are descriptive only to preserve a parsimonious statistical analysis of this extensive experimental design. For this same reason, the means reported on movement time, peak-velocity, and distances traveled by the hands are descriptive only. We verified that differences in task means did not result from large between-group differences by comparing the means of individuals to the task mean. As a rule, the individual means corresponded to the task mean. The significance level was set at .05.

**Results**

We start by giving a brief description of the general task performance and a characterization of task execution on the basis of individual velocity profiles and on the basis of the movement times and peak velocities. Subsequently, we discuss the displacement of the shoulders by presenting the results pertaining to the distances traveled by the shoulder between start and end of movement. The relationship between displacement of the shoulders and the fluency of the hand is then discussed. The sequencing of the hand and shoulder displacements is analyzed in two ways. First, we present the results of our analysis of onset sequencing and a discussion of the analyses of the standard deviation of this measure, which served as a measure of variability of the onset sequencing pattern. Second, we present the results of our analyses on peak sequencing and the variability of this measure.

**General Performance**

The participants were able to perform the tasks in 97% of the trials. Only 3% of the trials were classified as invalid due to extreme reaction times, extreme movement times or otherwise erroneous task execution. Mean distances traveled by the hand were 22, 30, and 38 cm for the hitting, reaching, and grasping tasks, respectively.

**Velocity Profiles of Individual Trials**

Figure 2 shows representative velocity profiles for both hands and both shoulders for trials performed during unimanual task execution (left panels) and for trials during bimanual task execution (right panels). The top two panels show trials in
the hitting task, the middle panels show trials from the reaching task, and the bottom panels show velocity profiles of trials from the grasping task. Several interesting effects become apparent from these figures. Typically, there is an asymmetry between the impaired and unimpaired hand when comparing them during unimanual task execution. This asymmetry largely disappears during bimanual task execution because the unimpaired hand adapts to the impaired hand. While in hitting movements the shoulders reach peak velocity before the hand reaches peak velocity, during reaching and grasping movements this pattern reverses. Also, the more or less bell-shaped velocity profiles observed in both the reaching and grasping tasks are not present in the hitting task. In the latter task, the impact with the screen ends the movement abruptly. There is less shoulder velocity in the hitting task compared to the other tasks but primarily during unimanual task execution.

*Movement Times*

We inspected the movement times as a general assessment of task performance. Mean movement times are depicted in Figure 3. The top panel presents the means for the hitting task, the middle panel presents the means for the reaching task, and the bottom panel presents the means observed in the grasping task. White bars represent means observed for the impaired hand, and black bars represent the means.

Figure 2 — Representative velocity profiles. The top two lines in each panel represent the velocity profiles of the two hands. The lower two lines in each panel represent the velocity profiles of the corresponding ipsilateral shoulders.
observed for the unimpaired hand. Within each panel, the four bars to the left are the means observed during unimanual task execution, while bars to the right represent means observed during bimanual task execution. Finally, adjacent bars of the same color represent from left to right means observed for large and small targets, respectively. This organization is used in all subsequent figures. Mean movement times were 540, 651, and 728 ms for the hitting, reaching, and grasping tasks, respectively. A difference in movement times between hands can be observed in

![Movement Time](image)

Figure 3 — Mean values and standard deviations across participants for the movement time as a function of hand, task execution, and target size (see text for the representation of the bars).
unimanual task execution. This difference disappears during bimanual task execution, as the unimpaired hand adapts to the movement time of the impaired hand.

**Displacement of the Shoulders**

Shoulder displacement was defined as the Euclidean distance traveled by the shoulder between the start and end of its movement. In Figure 4 (left panels), it can be seen that the shoulder displacement was 9 cm in the hitting task, 12 cm in the reaching task, and 15 cm in the grasping task. Given the mean hand displacements specified above, these shoulder displacements were regarded considerable (about 40% of hand displacement in each task). Furthermore, in all three tasks there was more shoulder displacement during bimanual task execution than in unimanual task execution. For the hitting, reaching, and grasping tasks the test statistics were $F_{1,5} = 15.88, p < .01; F_{1,5} = 19.01, p < .01$; and $F_{1,5} = 24.71, p < .01$, respectively. Although these effects can be attributed primarily to increases in the shoulder displacement of the unimpaired shoulder, the impaired shoulder also travels a greater distance during bimanual task execution in all three tasks and especially in the hitting task. During unimanual task execution, the impaired shoulder travels a longer

![Figure 4](image)

**Figure 4** — Mean values and standard deviations across participants for the distances traveled by the shoulders (left panels) as a function of hand, task execution, and target size. The panels to the right represent the mean number of peaks and valleys in the velocity profiles of the hand normalized in time as a measure of fluency of the hand. The means are displayed similarly to Figure 3.
distance compared to the unimpaired shoulder. The effect of hand used, however, is only significant for the reaching and grasping task, $F_{1,5} = 12.65, p < .05$ and $F_{1,5} = 16.52, p < .05$. A significant interaction between task execution and hand for all three tasks indicated that the between-arm difference in the distance traveled by the shoulders is different in the unimanual compared to the bimanual task execution. Statistics were $F_{1,5} = 7.65, p < .05$, $F_{1,5} = 12.58, p < .05$ and $F_{1,5} = 13.66, p < .05$, for the hitting, reaching, and grasping tasks, respectively. No significant effects on the shoulder displacement were observed as a function of target size.

**Dysfluency**

The dysfluency of hand movement, defined as the (time-normalized) number of peaks and valleys in the tangential velocity profile corresponding to the hand displacement, are depicted in the right-hand panels of Figure 4. The dysfluency values for the hitting, reaching, and grasping tasks were 10.43, 8.11, and 7.35 velocity-inversions/s, respectively.

In the hitting task target size caused significant variations in the dysfluency of the hand displacements. Smaller targets caused less fluent motions $F_{1,6} = 8.61, p < .05$. No main effects of task execution were observed. Thus, with respect to our hypothesis on the effects of variations in shoulder displacements on the fluency of the hand, it is important to note that the amount of dysfluency during unimanual versus bimanual task execution is not significantly different, while the distances traveled by the shoulders did vary significantly between these conditions.

In the reaching task, the impaired hand was less fluent compared to the unimpaired hand $F_{1,5} = 9.74, p < .05$. This was the case in both the unimanual and bimanual task execution. No other significant effects were observed. In the grasping task the hands differed only marginally $F_{1,5} = 6.17, p = .056$. No significant effects of task execution or target size were observed on our measure of dysfluency. Again, with respect to our hypothesis on the effects of shoulder displacement on hand fluency, we emphasize that the shoulder displacements varied as a function of task execution but hand fluency did not.

**Onset Sequencing**

From the mean values of onset sequencing shown in the left-hand panels of Figure 5, it can be seen that for all three tasks, the shoulder started to move before the hand started to move, (i.e., the mean values are positive). Also, note from the standard deviations that the variation among participants was large. The only significant effect was that the mean onset difference was larger for the unimanual task execution compared to the bimanual task execution in the hitting task $F_{1,6} = 8.73, p < .05$. Overall mean onsets differences per task were 52, 80, and 79 ms for the hitting, reaching, and grasping tasks, respectively.

**Variability of Onset Sequencing**

Much to our surprise the within-subject variability of the onset sequencing (depicted in the right-hand panels of Figure 5) of the impaired side was not significantly larger than that of the unimpaired side in any of the three tasks. This finding contradicts the conclusions of Archambault et al. (1999) that hemiparetic participants may have an impaired ability to consistently time hand and shoulder move-
ment onsets and also invalidates our prediction that the variability of the onset sequencing would be significantly increased.

**Peak Sequencing**

Whereas the onset sequencing pattern was equal across tasks, our measure of peak sequencing was clearly different between tasks (see left-hand panels in Figure 6). For the hitting task, the mean values of peak sequencing were positive, indicating that the hand reached peak velocity later than the shoulder. For the reaching and grasping task, the pattern was the opposite—that is, the hand reached peak velocity prior to the moment at which the shoulder reached peak (tangential) velocity. Also, the interval between peaks was larger in the grasping task compared to the reaching task. Mean peak sequencing values were +128, −121, and −145 ms for the hitting, reaching, and grasping tasks, respectively. It must be noted, however, that these values are not normalized. The relative peak sequencing pattern (thus, relative to movement time) for the reaching and grasping tasks were 121/651 = .186 and 145/728 = .199. Therefore, the relative peak sequencing patterns between reaching and grasping do not differ strongly. Still, a different peak sequencing pattern is

**Figure 5** — Mean onset asynchronies are shown in the left panels. The within-subject variability of the onset asynchrony is shown in the right panels. Error bars reflect between-subject variability (standard deviations). The means are displayed similarly to Figure 3.
apparent between the hitting task compared to the reaching and grasping task. Such a between-tasks difference was not present for the mean onset sequencing.

No main effects for hand, task execution, or target size were observed in the hitting task. In contrast, for both reaching and grasping, the peak sequencing pattern varied significantly as a function of hand and task execution. The statistics were $F_{1,5} = 25.98, p < .01$ and $F_{1,5} = 19.46, p < .01$ for the reaching task and $F_{1,5} = 16.74, p < .01$ and $F_{1,5} = 10.83, p < .05$ for the grasping task. For both reaching and grasping, the interval between tangential-velocity peaks is significantly longer in the bimanual task execution compared to the unimanual task execution. Furthermore, the impaired hand displays a significantly different sequencing pattern compared to the unimpaired hand; the time between peaks is significantly larger in the impaired hand. It might be argued that this absolute difference is confounded by the fact that the impaired hand moves slower compared to the unimpaired hand. Although this is true for unimanual task execution, during bimanual task execution the movement times of both hands are equal, while the difference in peak onset sequencing persists. Therefore, the between-arm difference in peak sequencing is significant. It is surprising that no interaction between hand and task execution was observed—that is, the between-arm difference did not vary as a function of

![Figure 6](image_url)

*Figure 6* — Mean peak-velocity asynchronies are shown in the left panels. The within-subject variability of the peak-velocity asynchrony is shown in the right panels. Error bars reflect between-subject variability (standard deviations). The means are displayed similarly to Figure 3.
task execution. It appears that the between-arm coupling in movement time during bimanual reaching and grasping is absent with respect to peak sequencing.

**Variability of Peak Sequencing**

Neither for the hitting nor for the reaching task did any of our experimental factors lead to significant differences in our measure of variability of peak-velocity sequencing. In the grasping task, however, there was a significant difference as a function of hand used. The impaired side displayed more variability compared to the unimpaired side, $F_{1,5} = 27.31, p < .01$. Moreover, this between-side difference was significantly larger during unimanual task execution compared to bimanual task execution $F_{1,5} = 8.62, p < .01$. Actually, the variability of the impaired side decreased during bimanual task execution, whereas the variability of the unimpaired side increased during bimanual task execution.

**Discussion**

In the present study, we examined in three different motor tasks performed by young adults with hemiparetic cerebral palsy, the recruitment of shoulder displacement, and its effect on hand fluency as well as the sequencing of the shoulder and hand displacements. In line with our expectations, the fluency of the impaired hand was not influenced by the amount of shoulder displacement. Especially in the hitting task, the impaired hand displayed an equal amount of dysfluency during unimanual versus bimanual task execution, while the distances traveled by the shoulders did vary significantly. The results indicate that the hemiparetic participants in the present study preserved invariance in terms of fluency of hand movement under variations of shoulder displacement as healthy participants do (Kaminski et al., 1995; Ma & Feldman, 1955; Marteniuk & Bertram, this issue; Saling et al., 1996).

The consistent increased dysfluency of the impaired hand compared to the unimpaired hand during unimanual reaching and grasping may be attributed to the fact that shoulder-elbow angular coordination in reaching and grasping is segmented (Steenbergen et al., 2000; see also Levin, 1996). Movements at the impaired side start primarily with a large shoulder flexion and elevation, followed by elbow extension. This is evidence for a proximal to distal movement unfolding, and it might well be that the transition between these joint regimes causes the decreased fluency of the impaired hand. This suggestion is strengthened by the analysis of temporal sequencing between shoulder and hand at movement onset and at peak velocity that was done in the present experiment. Furthermore, Van Thiel et al. (2000) showed that an increase in spatial variability may be a prime characteristic of hemiparetic movements. This may have contributed to a decrease of fluency in the impaired hand. Especially when task execution requires fine finger and hand manipulations (as in pushing a button and grasping blocks), between arm differences in fluency become apparent, since hemiparetic participants experience the largest difficulties with the control over distal components.

Besides examining the fluency of the hand as a function of shoulder displacement, the present study was also concerned with the temporal relationship (sequencing) between shoulder and hand displacement and the stability of this sequencing. We constructed two measures of sequencing—namely, movement onset and peak-velocity asynchrony. We discuss the onset sequencing first followed by the discussion of the peak sequencing.
It was generally found that the onset of shoulder displacement consistently preceded the onset of hand motion in all three tasks for both the impaired and the unimpaired hand (see Figure 4). Moreover, none of the task variables manipulated exerted any influence on the stability of this sequencing measure. This pattern resembles the onset sequence that has been observed in healthy participants (Ma & Feldman, 1995; and to a lesser degree Saling et al., 1996) but is dissimilar from that found by Archambault et al. (1999) in hemiparetic patients. In the latter study, patients started with either the hand or the shoulder. They were unable to stabilize the sequence of shoulder and hand movements within a set of trials. It must be noted that a possible drawback of the study of Archambault et al. (1999) is that participants were instructed to restrict any rotational movements of the shoulders (only forward and backward movements were allowed) and that participants were explicitly instructed to move the shoulders together with the hand in the in-phase and out-of-phase conditions. Perhaps these restrictions and instructions influenced task performance negatively, since we have shown in a recent study (Steenbergen et al., 2000) that in reaching and grasping movements in hemiparesis a considerable part of shoulder displacement is due to rotations of the trunk. This suggests that restricting motion of the shoulders to forward motion only might hinder the natural tendency in hemiparetic participants to make use of rotation and, in the worst case, force participants into difficult and unwanted movement patterns. In line with Marteniuk and Bertram (this issue), we therefore strongly plead for the study of unrestricted movements to explore the full adaptive capacity of the disordered movement system.

In peak sequencing we observed in the reaching and grasping tasks effects of both hand and task execution. In our opinion, this may reflect the natural preference of the impaired movement system to adapt to the constraints imposed (cf. Latash & Anson, 1996). This implies that participants with hemiparetic cerebral palsy are capable of finding a solution to the degrees of freedom problem, but they solve it differently for their impaired side than for their unimpaired side. Furthermore, since both hands showed similar variabilities of the peak sequencing patterns for the hitting and reaching task and similar variabilities of the onset sequencing for all three tasks, we conclude that the sequencing patterns that were realized were stable (i.e., invariable) yet different between the hands. These results challenge the conclusions of Archambault et al. (1999) that the recruitment and sequencing of the different degrees of freedom in hemiparetic individuals may be impaired. We must stress, however, that their conclusions are based upon comparisons between healthy and hemiparetic movements, whereas our conclusions are based upon comparisons between movements of the unimpaired and impaired side within the same participants. It is a well-established fact that the unimpaired arm of hemiparetic participants also displays deficits (Baldiserra et al., 1994; Thilmann et al., 1990; Van Thiel et al., 2000). Still, between-arm comparisons in hemiparetic cerebral palsy are very informative, especially when clear between arm differences exist as was the case in the present study. In this light we can still conclude that under unrestricted movement conditions, the sequencing of impaired shoulder and hand motion in participants with hemiparetic cerebral palsy may be optimal; stable and functional solutions are achieved.

Only in one instance did our results suggest that the sequencing of degrees of freedom might be impaired in hemiparesis. For the grasping task, the peak-velocity sequencing pattern for the impaired arm was significantly more variable compared to the unimpaired arm but only during unimanual task execution. It is
well established that a strong coupling in time exists between the moment of peak velocity of a movement and the moment of maximum aperture in grasping tasks (Jeannerod, 1988). This is the case in both healthy and hemiparetic movements. Furthermore, hemiparetic participants experience the strongest difficulties with the control over the distal musculature (i.e., the fingers and the hand), which is specifically required in grasping (see e.g., Steenbergen et al., 1998, 2000). Realizing that our measure of peak sequencing depends directly upon the moment of peak velocity, which correlates strongly with moment of maximum aperture, it is no surprise that significant increases in variability for the impaired hand are only observed in the grasping task. Therefore, the finding that the variability of the peak sequencing pattern of the impaired hand is increased in unimanual grasping does not contradict our views on the ability of participants with hemiparetic cerebral palsy to recruit and sequence their degrees of freedom to perform arm movements.

During bimanual grasping, there was no difference between the hands with respect to the variability of peak sequencing. Compared with unimanual task execution, the variability of the impaired hand decreases during bimanual task execution, whereas the variability of the unimpaired hand increases. These observations might present evidence for a between-hands coupling with respect to the moment of maximum aperture and therefore also the moment of peak-velocity. This effect is even more surprising when we realize that the between hands difference in peak sequencing patterns persisted during bimanual task execution. Perhaps it suggests that control over the moment of maximum aperture is unrelated to the control mechanisms determining the peak sequencing pattern. Although this reasoning is speculative only, it may well be a very interesting topic for further investigation, especially since any possible beneficial transfer effect from the unimpaired hand to the impaired hand can be of great advantage in the rehabilitation and training of people with hemiparetic cerebral palsy.

In sum it appears that participants with hemiparetic cerebral palsy experience no difficulties with finding solutions to the degrees of freedom problem (Bernstein, 1967) when making movements with their impaired arm. We find that, although different solutions are accomplished with the impaired arm, these solutions are not affected by the disorder in the sense that they are more variable (i.e., unstable) compared to the unimpaired arm. Also, the observation that our measurements of hand movement fluency did not vary as a result of increases in shoulder movements suggests that these participants preserve the ability to maintain end-effector invariance as healthy participants do. Adaptations to the disorder do give rise to differences in task execution and thereby in task performance, but shoulder displacement remains an integral part of arm movements in hemiparetic cerebral palsy, albeit in different magnitudes and differently sequenced.

References


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