The coordination of reaching and grasping in spastic hemiparesis

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Abstract

The kinematics and intrinsic dynamics of reaching and grasping movements in six subjects with spastic hemiparesis were studied. Movements were performed with both hands together as well as with each hand in isolation, and two target widths were used. As expected, large manual asymmetries existed in unimanual task performance. These asymmetries were more pronounced for grasping than for reaching, which was a consequence of the fact that in grasping the impaired hand stayed longer at zero velocity before lifting the object. This implies difficulties coordinating the more distal movement component (hand and fingers). In addition, the impaired hand attained the movement goal with a (1) decreased angular range of motion of the joints and (2) an increased trunk involvement. With respect to the intrinsic dynamics, intra- and inter-limb coupling was studied by evaluating cross-correlations of position–time functions joint pairs. In effector space the displacement of the wrist and ipsilateral shoulder were correlated, and in joint-angle space the elbow extension–shoulder flexion angle pair and the elbow extension–shoulder elevation angle pair were analysed. It was found that despite tight couplings between the different pairs, the coupling strengths for the impaired limb were consistently lower. This was caused by fragmentation of the movement, mainly due to a large shoulder involvement at the start of the movement concurrent with little or no elbow extension. It is concluded that fragmentation of the movement, operationalised by the...
value of the cross-correlation between joint pairs is an essential variable by which the level of recovery of function can be captured. It was further shown that the unimpaired hand ‘mimicked’ the impaired hand on a number of movement characteristics under bimanual responding. The impaired hand did not change its style of movement organisation among uni- and bimanual movement responding. It is argued that the apparent stability of the impaired hand can only be sustained at the cost of a decreased flexibility. Finally, inter-limb coupling, assessed by means of cross-correlations of the tangential velocity profiles of both hands, was shown to be high during the course of movement. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Reaching and grasping movements require the integration of trunk, arm and hand displacements into a smooth movement. The production of smooth movements is obviously impaired in subjects with spastic hemiparesis. In spite of its acute clinical (i.e., diagnostic and therapeutic) significance, the study of the underlying coordination pattern in these subjects has only received scant attention (for an exception, Levin, 1996). Meanwhile, other descriptions of disordered movement control do exist, but are confined to different levels of observation.

The most frequently used level of observation in clinical settings is that of performance outcome scores. For the assessment of dexterity for example, a great variety of tests is available to the practitioner. A potent shortcoming of the majority of these tests, however, is that they solely provide information on speed of the task performance (McPhee, 1987). As a consequence, it is difficult to focus therapy on those aspects of manual control that hinder skillful performance. Therefore, once the level of dexterity has been diagnosed, one needs to go beyond this level of appraisal to find out why performance is deficient (Wann et al., 1998).

Another level of observation is the examination of the kinematics of the impaired effector-system. Trombly (1992), for instance, compared isolated reaching movements of the impaired arm with those of the unimpaired arm in subjects with left hemiplegia. In addition to a prolonged movement time, the impaired arm displayed more movement units as assessed by studying the acceleration profiles of the hand. Trombly (1992) argued that this
finding indicates a discontinuous movement strategy, possibly due to a combination of muscle weakness and disturbed sensorimotor processes in the arm. The weakness might also explain the lower peak velocities of the impaired hand found in four out of five subjects. Recently, Roby-Brami et al. (1997) studied patients with vascular hemiplegia when reaching movements were made to a light cone placed at one of seven positions on a baseboard. In addition to recording the displacement of the wrist, trunk involvement was also assessed. Again, prolonged movement times and lowered peak velocities were found for the impaired side compared to the unimpaired side. It was also shown that the contribution of trunk movement towards movement completion was larger for the impaired side. Still, neither in this study, nor in that of Trombly (1992) any analyses were performed on the coordination patterns underlying these movements. Such analyses will be the focus of the present study.

Although coordination seems to be disturbed in spastic subjects, these subjects are able to show some form of coordination between both hands during bimanual responding as evidenced by a high temporal invariance at the end of the movement (Steenbergen et al., 1996). The asymmetry present between both hands in unimanual movement conditions is annihilated to a great extent during bimanual movement conditions, because the unimpaired hand adopts the time scale of the impaired hand in these instances. A similar inter-limb coupling has been found by Sugden and Utley (1995), although the manner in which the coupling was achieved in their study was more heterogenous across subjects. These studies indicate that even for spastic hemiparetic subjects, the temporal and spatial constraints of a bimanual act shape the execution of simultaneous actions as they do in control subjects without neurological deficits (Kelso et al., 1983). The results of the previous study (Steenbergen et al., 1996) further suggest that the asymmetry between both limbs could for a large part be attributed to difficulties in controlling the more distal musculature of the impaired hand. Indeed, this facet of response execution was prolonged disproportionally in the impaired limb during grasping movements (Steenbergen et al., 1998; see also Eliasson et al., 1991). While grasping involves a complex interplay between arm movement and fine control of the hand and fingers (distal musculature), reaching is primarily accomplished by the arm (proximal musculature) with the finger being a simple extension of the arm. Therefore, we compared grasping with reaching movements in the present study under the assumption that the manual asymmetries would be reduced during reaching.
We also sought to characterise both limbs in terms of their intrinsic dynamics. Is there evidence to suggest that the limbs may be differentiated on the basis of their intrinsic dynamics? Moreover, does the intrinsic dynamics of the impaired limb change when it is engaged in a cooperative action together with the unimpaired limb? A dynamic analysis of both hand systems as reflected in the coordination patterns necessitates the identification of one or more order parameters (Schöner and Kelso, 1988). In cyclical movements, the relative–phase relationship between joints has been identified as an appropriate order parameter that describes the system’s intrinsic dynamics (e.g. Kelso et al., 1991 for single-limb movements; Baldiessera et al., 1991; Wagenaar and Van Emmerik, 1994 for multi-limb movements). Another candidate is the coupling strength between joint angles or between limb-segment trajectories (e.g. Newell and Van Emmerik, 1989; Van Emmerik and Newell, 1990; Vereijken et al., 1992; Steenbergen et al., 1995; Temprado et al., 1997). Novice sporters (Vereijken et al., 1992; Temprado et al., 1997) and less proficient movement systems (Newell and Van Emmerik, 1989; Van Emmerik and Newell, 1990; Steenbergen et al., 1995) display a higher degree of joint coupling, or ‘freezing’ (cf. Bernstein, 1967). Thus, joint coupling might be considered an essential variable on the basis of which movement systems can be discriminated. In the present study, the absolute values of the cross-correlations between the joint pairs are used as an index of the degree of joint coupling. A value near 1 implies a tight coupling between the joints, whereas a value near 0 indicates independent control. Recently, Levin (1996) showed that interjoint coordination between the elbow and shoulder joint of the impaired arm of a group of hemiparetic subjects is disrupted. The paths of angle–angle position–time functions displayed deviations from a straight line and were fragmented. This fragmentation might point to independent control of the joints.

In the present study, we examined the limb dynamics of both limbs of spastic hemiparetic subjects under various task constraints. Coupling strength in each limb was assessed by means of the value of the cross-correlation between joint linkages, both, in effector space and in joint-angle space. In addition, kinematic characteristics of the end effector and the contribution of the trunk to movement completion were studied. Finally, we also examined coupling strength between both limbs (inter-limb coupling) during the ongoing movement. A high temporal invariance between both limbs during bimanual task performance was expected to be found (Steenbergen et al., 1996; Sugden and Utley, 1995).
2. Participants and method

2.1. Participants

The experimental group consisted of six subjects with spastic hemiparesis (mean age 17.3 years, S.D. 1.6 years). For five subjects the hemiparetic side was the left side, and for one subject it was the right side (see Table 1 for subject information). All subjects were diagnosed as having developed spasticity and had gone through extensive rehabilitation programs. Their condition was described as stable. Subjects were recruited from the Werkenrode Institute, where they followed an adapted teaching program. Initially, a group of 10 subjects was tested. However, four subjects could not reliably grasp the objects and were excluded from further experimentation. Subjects gave signed consent prior to testing.

2.2. Task, apparatus and experimental procedure

Participants sat comfortably at a table and had to perform reaching and grasping movements with the impaired arm, the unimpaired arm, and with both arms simultaneously (Experimental set-up, see Fig. 1).

In the reaching task, subjects had to reach to a box and push a red circular disc on top of it. Microswitches underneath the box registered moment of contact. Two target sizes were used in the experiment (Large and Small; discs of 50 and 30 mm in diameter, respectively). In the grasping task two blocks were used that were both 60 mm in height and 30 mm in depth. Two block sizes were used; a large one having a width of 50 mm and a small one, with a width of 30 mm. The blocks rested on a metal plate linked to the computer. At the bottom of the blocks a plate of metal foil was attached to detect the moment the block was picked up.

Table 1
Overview of subject information

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (years)</th>
<th>Diagnosis</th>
<th>Aetiology</th>
<th>Other</th>
</tr>
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<tbody>
<tr>
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<td>Cerebral palsy</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>18.6</td>
<td>Right spastic hemiparesis</td>
<td>Cerebral palsy</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>17.2</td>
<td>Left spastic hemiparesis</td>
<td>Viral meningitis</td>
<td>during first year</td>
</tr>
<tr>
<td>4</td>
<td>16.3</td>
<td>Left spastic hemiparesis</td>
<td>Cerebral palsy</td>
<td>Epileptic</td>
</tr>
<tr>
<td>5</td>
<td>18.2</td>
<td>Left spastic hemiparesis</td>
<td>Cerebral palsy</td>
<td>Mild dysarthria</td>
</tr>
<tr>
<td>6</td>
<td>14.5</td>
<td>Left spastic hemiparesis</td>
<td>Cerebral palsy</td>
<td>–</td>
</tr>
</tbody>
</table>
The experimental set-up was similar in all conditions (see Fig. 1). Prior to testing subjects were seated properly on a chair. Care was taken with this installation as improper seating could lead to involuntary and unwanted
spastic synergies and early fatigue. At the start of a trial subjects rested both hands on start boxes (100 mm in length and 50 mm wide), under which switches were placed that registered movement onset. The starting location of the hand was along the body midline of the seated subject. The distance between the start boxes and the objects to be reached/grasped was 300 mm. Small red lights imbedded in the table top, placed just in front of the objects to be reached or grasped, indicated which hand(s) was (were) to be used in the trial. In the unimanual movement conditions the light corresponding to the hand to be used was lit at the start of a trial. In the bimanual movement conditions both lights were lit synchronously at the start of the trial. A computer-generated beep (GO signal) indicated to start the movement. Both the GO signal and the lights were activated simultaneously.

Infrared light emitting diodes (IREDs) were placed on the wrist, elbow and shoulder of both arms (see Fig. 1). An Optotrak 3020 system was used for 3D-motion recording. Standard errors of measurement were less than 0.2 mm in X, Y and Z directions. The Optotrak system sampled IRED coordinates at a rate of 200 Hz which were stored on a personal computer that also (1) activated the stimulus LEDs, (2) presented the acoustic signals, and (3) detected missing data points after each trial. Incomplete or otherwise incorrect trials were repeated immediately.

2.3. Instructions

Basic instructions for both tasks were alike. Subjects had to complete the task as accurately and as quickly as possible following the GO signal. In the reaching task subjects had to point at the target as quickly as possible. In the grasping task subjects were instructed to reach and grasp the objects, as quickly as possible, lift it to a preferred height and subsequently place it back. At the end of each trial subjects were required to place both hands back on the starting boxes. Following that, a random interval between 2 and 5 seconds preceded the next trial.

2.4. Design and data analysis

The experimental set-up provided 12 unique experimental conditions determined by: Task, Movement Condition, Hand Used, and Target Size. There were blocks of 12 trials in each experimental condition. Reaching and grasping were tested in separate blocks of trials and the order of testing was counterbalanced across subjects. Within such a Task block, trials were
further blocked according to the factor Target Size. The order of these blocks was also changed across subjects. Within these ‘basic’ blocks a total of 36 randomized trials were performed (12 with each hand in isolation and 12 with both hands together). For each dependent measure, the average for each condition pooled across replications was analyzed separately using a repeated measures analysis of variance design with the following factors; Movement Condition [unimanual vs. bimanual], Hand [unimpaired vs. impaired], Target size [50 mm vs. 30 mm], Task [reaching vs. grasping]. Post hoc comparisons were performed using Newmann–Keuls routines. Significance level was set to 0.05.

Following data collection, the raw data files were converted into 3D co-ordinates. The principal movement axis was the $y$-axis (see Fig. 2). Data were filtered by means of a second-order Butterworth filter with a dual pass and at a cut-off frequency of 7 Hz. Analysis of the data was divided into four steps. First, the temporal characteristics of the movements were analysed. Second, the displacement of both shoulder markers in the main movement direction

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**Fig. 2.** Definition of the cardinal axis (top) and the joint angles (bottom). Bottom left: the left arm in isolation; bottom middle: shoulder flexion ($\phi$); bottom right: shoulder elevation ($\epsilon$).
(y-axis) were calculated such that postural involvement with respect to trunk translation and trunk rotation could be assessed. In the third step, the kinematics of the end effector were analysed, followed by a fourth step which was concerned with the intrinsic dynamics of both limbs.

First, three joint angles were defined; elbow angle (this angle was constructed by linking the wrist and elbow marker, and the elbow and shoulder marker to line segments, and consequently calculating the angle between them), and two shoulder angles. The first shoulder angle was flexion and was defined in the $XY$-plane and the second shoulder angle was elevation and defined in the $YZ$-plane (see Fig. 2). Second, for each individual movement, angular change for all three joints was calculated. This was carried out by subtracting the angle at the start of the movement from the angle at the end of the movement.

Third, intra-limb coordination was established both, in effector space and in joint-angle space. With respect to the effector space we calculated the cross-correlations between the resultant displacements of the wrist and ipsilateral shoulder. Intra-limb coordination in joint-angle space was determined by calculation of the within-trial cross-correlation between elbow extension–shoulder flexion and elbow extension–shoulder elevation. Finally, in the bimanual movement conditions, inter-limb coupling between both end effectors was determined via the calculation of within-trial cross-correlations between the resultant velocity profiles of both end effectors. For each condition, correlations were averaged and analysed following a Fisher-Z transformation.

3. Results

3.1. Temporal characteristics of the movement

As was explained in Section 2, we determined the end of the task by contact breaking signals. For the reaching task this was the moment at which the circle on the box was pressed and for the grasping task it was the moment at which the block lost contact with the table top, i.e. was lifted. In a previous study, it has been shown that the impaired limb of hemiparetic subjects needed a disproportional long time in contact with the object before lifting it (Steenbergen et al., 1998), indicating distal control problems. To verify this phenomenon, we compared the velocity profiles of movement performance on the reaching task with that on the grasping task.
Shown in Fig. 3(a)–(d) are representative resultant velocity profiles of the wrist for one subject. The two top figures (Fig. 3(a) and (b)) show resultant velocity profiles of the unimpaired wrist in the reaching and grasping task, whereas Fig. 3(c) and (d) show the resultant velocity profiles of the impaired wrist in the reaching and grasping task, respectively. The resultant velocity profiles are shown until the moment of impact for the reaching task (Fig. 3(a) and (c)) and until the object is lifted for the grasping task (Fig. 3(b) and (d)).

Fig. 3(a) shows that for the reaching movements performed with the unimpaired wrist, the target was pressed ‘on flight’, hence, before velocity reached zero. This was not essentially different for the impaired limb (Fig. 3(c)). Yet, velocity of the impaired wrist was closer to zero at the moment of impact, indicating a more careful approach to the target. Grasping with the unimpaired hand revealed a similar movement pattern (Fig. 3(b)). However, a different picture emerges for grasping with the impaired hand (Fig. 3(d)). For this limb, velocity of the wrist reached zero, after which a considerable period of time is spent close to the object before it is lifted. This period reflects the time necessary for the proper positioning of hand and fingers and for
attaining a firm grasp of the object before lifting it. In other words, with this hand subjects have difficulties controlling the more distal musculature.

To test this notion more systematically, we compared movement duration assessed via the contact breaking signals (denoted ‘Task end’) with movement duration assessed via the velocity profiles of the wrist (denoted ‘Zero velocity’). For the latter assessment, semi-automatic segmentation routines were used. Peak velocity of the wrist marker was determined and the first moment at which velocity reached 5% of peak velocity afterwards was denoted Zero velocity. In the case 5% was reached earlier than the end of the movement via contact breaking, the Zero velocity value was used in the analysis. Obviously, contact breaking also occurred before velocity reaching 5% of peak velocity (see for instance, Fig. 3(a)). If this was the case, the value of contact breaking was used. Fig. 4(a) and (b) show the results of this analysis for reaching and grasping, respectively.

Clearly, in all reaching conditions (Fig. 4(a)), and in the unimanual grasping conditions with the unimpaired hand (Fig. 4(b)) not much time was spent after Zero velocity before the object was pressed, or lifted as signified by the short time span between Zero velocity and Task end. In sharp contrast, when moving in isolation, the impaired hand spent a considerable period after Zero velocity before the object was lifted. Strikingly, the unimpaired hand adopted a similar temporal pattern during bimanual responding. That is, Zero velocity was reached almost simultaneously with the impaired hand, as well as the end of the complete task. In the light of the results found for the unimpaired hand in the unimanual grasping conditions, it is clear that the unimpaired hand ‘waits’ for the impaired hand before the object is lifted.

Statistical analysis performed on both temporal measures confirmed these observations. There was a significant main effect of Task ($F(1,10) = 6.19, P < 0.05$) as well as an interaction of Task X Hand ($F(1,10) = 6.61, P < 0.05$) on the variable Task end. Grasping had a longer duration than reaching, and this effect was primarily the result of an increase in movement duration of the impaired hand. For movement duration established via Zero velocity, however, these effects disappeared. Hence, the enlarged asymmetry between both limbs during grasping movements is the result of a lengthening of the time spent after zero velocity by the impaired hand during grasping, signifying distal movement problems.

In addition, for both, Task end as well as Zero velocity, the impaired hand was slower than the unimpaired hand ($P < 0.001$) and unimanual movement condition were of shorter duration than bimanual movement conditions ($P < 0.01$). Also, for both dependent variables, post hoc analysis of the Hand
Fig. 4. Duration of the movements calculated on the basis of the resultant velocity profiles of the wrist (‘Zero velocity’) and on the basis of contact breaking signals (‘Task end’; see text for details). Displayed in (a) are the movement durations in the reaching task and in (b) the durations in the grasping movements.
X Condition interaction showed that the movement time of the impaired hand did not differ across unimanual and bimanual responding. The movement time of the unimpaired hand, nevertheless, was prolonged in comparison to that of the impaired hand during bimanual responding (see Fig. 4(a) and (b)). Hence, despite the fact that the unimpaired hand was quicker when moving in isolation, this hand slowed down to adopt the time scale (and timing pattern) of the impaired hand during bimanual movements.

3.2. Trunk involvement

The contribution of the trunk to the movement goal was assessed via the displacement of both the ipsilateral shoulder marker and the contralateral shoulder marker in the principal movement axis (Y-direction, see Fig. 2). In addition, the difference between ipsilateral and contralateral shoulder displacement was calculated to disentangle trunk rotation from trunk translation. Fig. 5(a) and (b) show the displacement of the ipsilateral and contralateral shoulder in the Y-direction for reaching (Fig. 5(a)) and grasping (Fig. 5(b)), respectively.

As can be seen in Fig. 5(a) and (b) and confirmed statistically ($F(1,10) = 58.30, P < 0.001$), the contribution of the ipsilateral shoulder was larger for the impaired side than for the unimpaired side. Also, the ipsilateral shoulder contribution was larger in the bimanual conditions compared to the unimanual conditions ($F(1,10) = 43.12, P < 0.001$). The latter effect, however, was the result of an increased ipsilateral shoulder contribution to the movement of the unimpaired side under bimanual responding (Hand X Condition interaction; $F(1,10) = 66.50, P < 0.001$).

For the contralateral shoulder displacement the effects were alike. Thus, a larger involvement on the impaired side ($F(1,10) = 24.42, P < 0.001$), and a larger involvement under bimanual movement conditions ($F(1,10) = 78.68, P < 0.001$). The latter was principally due to an increase of shoulder involvement to the movement of the unimpaired side in bimanual movement conditions ($F(1,10) = 33.99, P < 0.001$). Finally, the displacement of this shoulder was larger for grasping than for reaching ($F(1,10) = 6.24, P < 0.05$).

We also sought to determine the contribution of trunk rotation to movement completion. To that aim, the difference in displacement between shoulders in the Y-direction was calculated. Very clearly, the difference in the bimanual conditions was very small (maximum of 8 mm for the impaired hand during bimanual responding), and was larger in the unimanual move-
ment conditions (up to 80 mm for the impaired hand during grasping in the unimanual movement conditions, see Fig. 5(b)). This was confirmed statistically ($F(1, 10) = 40.76, P < 0.001$). No effects were found for the factor
Hand. Despite large differences in y-displacement between both shoulders during movements of the impaired and unimpaired side, no rotation differences between both sides were found. Hence, the increased involvement of the trunk for the impaired side compared to the unimpaired side was due to an extra translation movement of the trunk on top of the (basic) rotation. In the bimanual movement conditions, virtually no rotation occurred and most of the trunk involvement was the result of a translation movement (see Fig. 5(a) and (b)). There existed only a marginal effect of target size on the difference in shoulder displacement $F(1, 10) = 5.21, P < 0.05$. The difference for the large target was 31.7 mm, whereas this difference was 33.3 mm for the small target.

3.3. Kinematic characteristics of the end effector

Table 2 sums up the different kinematic variables calculated for the end-effector.

For the variable peak velocity, no differential results were found with respect to the hand used. The only effect found for this variable was attributable to Condition ($F(1, 10) = 6.89, P < 0.05$). Peak velocity was higher in unimanual conditions (820 mm/s) compared to the bimanual conditions (736 mm/s). The time to reach peak velocity was also different under unimanual and bimanual responding (460 ms vs. 515 ms: $F(1, 10) = 17.72, P < 0.01$). In addition, subjects reached peak velocity sooner with the unimpaired hand (386 ms) than with the impaired hand (588 ms; $F(1, 10) = 16.39, P < 0.01$). The near significant Hand X Condition interaction ($F(1, 10) = 4.81, P = 0.053$) showed that the latter effect could be attributed to the unimpaired hand. For this hand, the time to reach peak velocity was prolonged under bimanual responding up to the level of that of the impaired hand.

When time to reach peak velocity was evaluated with respect to the total movement time, resulting in a skewness measurements of the velocity profile, then the effect of hand disappeared. There existed a main effect of Condition on skewness ($F(1, 10) = 6.94, P < 0.05$). Post hoc analysis of the Hand X Condition interaction ($F(1, 10) = 25.59, P < 0.001$) indicated that the impaired hand did not change its style of organisation across unimanual and bimanual responding and displayed virtually symmetrical velocity profiles (49.1% and 51.6%, respectively). Whereas, the velocity profile of the unimpaired hand was more skewed to the right in the bimanual conditions (41.1%) compared to unimanual responding (54.6%).
The analysis of mean velocity showed a higher mean velocity of the unimpaired hand as compared to the impaired hand ($F(1,10) = 6.44$, $P < 0.05$). Mean velocity was also higher in the unimanual conditions compared to the bimanual conditions ($F(1,10) = 16.31$, $P < 0.01$). Post hoc analysis of the Hand X Condition interaction ($F(1,10) = 44.62$, $P < 0.001$) showed that the mean velocity of the unimpaired hand, when moving in isolation, was highest (462 mm/s), and dropped significantly in the bimanual conditions (346 mm/s). Mean velocity of the impaired hand, on the other hand, did not differ between unimanual (376 mm/s) and bimanual (382 mm/s) responding. Finally, post hoc analysis of the significant Hand X Task interaction ($F(1,10) = 5.09$, $P < 0.05$) showed that mean velocities of both

<table>
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<tr>
<th>Kinematics</th>
<th>Preferred hand</th>
<th>Impaired hand</th>
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<tbody>
<tr>
<td></td>
<td>Unimanual</td>
<td>Bimanual</td>
</tr>
<tr>
<td><strong>Peak velocity (mm/s)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reaching</td>
<td>776 (232)</td>
<td>660 (240)</td>
</tr>
<tr>
<td>Grasping</td>
<td>904 (280)</td>
<td>778 (254)</td>
</tr>
<tr>
<td><strong>Time to peak velocity (ms)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reaching</td>
<td>321 (41)</td>
<td>414 (171)</td>
</tr>
<tr>
<td>Grasping</td>
<td>356 (72)</td>
<td>455 (150)</td>
</tr>
<tr>
<td><strong>Skewness (%)</strong></td>
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<tr>
<td>Reaching</td>
<td>59.5 (7.8)</td>
<td>47.9 (8.2)</td>
</tr>
<tr>
<td>Grasping</td>
<td>49.7 (4.7)</td>
<td>34.2 (6.6)</td>
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<tr>
<td><strong>Mean velocity (mm/s)</strong></td>
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<tr>
<td>Reaching</td>
<td>444 (166)</td>
<td>348 (194)</td>
</tr>
<tr>
<td>Grasping</td>
<td>480 (170)</td>
<td>344 (124)</td>
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<tr>
<td><strong>Number of zero crossings</strong></td>
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<tr>
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<tr>
<td>Grasping</td>
<td>2.1 (1.0)</td>
<td>7.1 (2.1)</td>
</tr>
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**Angular change (in degrees)**

<table>
<thead>
<tr>
<th>Elbow extension</th>
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<tbody>
<tr>
<td>Reaching</td>
<td>39.0 (8.7)</td>
<td>28.8 (9.0)</td>
<td>25.7 (10.2)</td>
<td>25.2 (8.2)</td>
</tr>
<tr>
<td>Grasping</td>
<td>49.5 (11.0)</td>
<td>23.7 (12.8)</td>
<td>28.1 (8.4)</td>
<td>25.1 (10.9)</td>
</tr>
</tbody>
</table>

**Shoulder flexion**

| Reaching        | 50.0 (18.1)    | 39.0 (16.5)    | 36.9 (18.8)    | 35.8 (16.2)    |
| Grasping        | 56.5 (19.5)    | 26.7 (24.5)    | 55.8 (32.3)    | 47.4 (20.4)    |

**Shoulder elevation**

| Reaching        | 32.0 (11.8)    | 23.7 (9.8)     | 22.9 (6.6)     | 19.6 (4.4)     |
| Grasping        | 41.9 (19.2)    | 23.9 (22.2)    | 29.5 (7.1)     | 22.8 (5.9)     |
hands were similar for reaching, but that the unimpaired hand had a higher mean velocity in the grasping task compared to the impaired hand.

Finally, to gain insight into the fluency of end effector movement, the number of zero crossings in the acceleration profile was calculated. Zero crossings in this profile represent velocity changes, with a small number being an indication of fluent movements (e.g. Steenbergen et al., 1995). It was evident that the number of zero crossings in the grasping task was higher than in the reaching task \( F(1,10) = 12.61, \ P < 0.01 \). Also, it was higher for the impaired hand (7.2) compared to the unimpaired hand (3.4, \( F(1,10) = 107.55, \ P < 0.001 \)) and higher in the bimanual movement conditions compared to the unimanual movement conditions \( F(1,10) = 18.17, \ P < 0.01 \). Post hoc analysis of the significant Hand X Condition interaction \( F(1,10) = 56.34, \ P < 0.001 \) revealed that the number of zero crossings for the unimpaired hand in the unimanual conditions was smallest (1.7) and that this number increased up to the level of the impaired hand under bimanual responding (5.2). For the impaired hand no difference in number of zero crossings existed between unimanual and bimanual responding (7.3 and 7.2, respectively).

3.4. Intrinsic dynamics

In this final results section, the intrinsic dynamics of the unimpaired and impaired limb under the different movement conditions imposed is examined. The analysis on angular change in the different joints is presented first, followed by the analysis on the intra-limb coordination in effector space. In addition, the analysis on intra-limb coordination in joint-angle space is presented, followed by the final section in which the analysis on inter-limb coordination in bimanual movement conditions is shown.

4. Angular change

The angular changes of the different joints is displayed in the lower part of Table 2. It was clear that the angular motion of the impaired elbow was smaller (26.0°) than the unimpaired elbow (35.3°: \( F(1,10) = 13.10, \ P < 0.01 \)). Also, angular change in the elbow was smaller in bimanual (25.7) compared to unimanual (35.6) movement conditions \( F(1,10) = 18.76, \ P < 0.01 \). Post hoc analysis of the significant Hand X Condition interaction \( F(1,10) = 32.82, \ P < 0.001 \) showed that the unimpaired hand displayed
the largest amount elbow extension in the unimanual movement conditions (44.3°). In the bimanual movement conditions, elbow extension of this hand decreased to 26.3°, an amount similar to that of the impaired hand in both unimanual (26.9°) and bimanual (25.1°) conditions.

Shoulder flexion was also larger in the unimanual (49.8°) compared to the bimanual movement conditions (37.2°; F(1, 10) = 10.86, P < 0.01). Post hoc analysis of the Hand X Condition interaction (F(1, 10) = 21.56, P < 0.001) showed that the flexion of the unimpaired shoulder was largest under unimanual responding (53.3°) and smallest under bimanual conditions (32.9°). No difference in shoulder flexion across unimanual and bimanual conditions was present for the impaired hand (46.4° vs. 41.6°).

Similar to shoulder flexion, shoulder elevation was larger in the unimanual conditions (31.8°) compared to the bimanual conditions (22.5°: F(1, 10) = 32.07, P < 0.001). Post hoc analysis of the Hand X Condition interaction (F(1, 10) = 16.08, P < 0.01) revealed that this effect was the result of an increased shoulder elevation of the unimpaired hand under unimanual responding.

### 4.1. Intra-limb and inter-limb coordination

In Table 3, the results of the analysis on intra-limb and inter-limb coordination are shown. With respect to intra-limb coordination, the mean correlation coefficients collapsed over subjects are shown for the wrist trajectory–shoulder trajectory coupling, elbow extension–shoulder flexion coupling and elbow extension–shoulder elevation coupling. With respect to inter-limb coordination, mean correlation coefficients collapsed over subjects are shown for the resultant velocity profiles of both wrists in bimanual movement conditions. Also shown in Table 3 are the within-subject variation and the between-subject variation.

### 4.2. Intra-limb coordination in effector space

Clearly, all correlation values were very high, indicating a tight linkage between the movement of the wrist and that of the ipsilateral shoulder. There existed a significant Condition effect (F(1, 10) = 73.43, P < 0.001) as well as a significant Hand X Condition interaction (F(1, 10) = 36.70, P < 0.001). Post hoc analysis of this interaction revealed that the highest correlation value was present for the unimpaired hand when it moved in isolation. For the standard deviation, a near significant Hand effect (F(1, 10) = 4.92, P < 0.051)
was found. The standard deviation was lower for the impaired hand (0.016) compared to the unimpaired hand (0.023). No further effects were found.

In Fig. 6(a)–(d) representative position–position plots of the wrist and ipsilateral shoulder for one subject during grasping are shown. As can be seen in Fig. 6(a), a high correlation coefficient is represented by a virtually straight line in position–position space. A lower correlation coefficient, on the other hand, is caused by a slight fragmentation of the movement. As an illustration, Fig. 6(c) shows that the low correlation is caused by the fact that there is an increase in shoulder movement towards the end of the movement, while almost no movement of the wrist is present that stage.

### Table 3

Intra-limb coordination and inter-limb coordination. (Displayed are the mean correlation coefficients collapsed over subjects in the different movement conditions. Also displayed are the mean within-subject standard deviation and the mean between-subject standard deviation)

<table>
<thead>
<tr>
<th></th>
<th>Preferred hand</th>
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<th>Impaired hand</th>
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<td></td>
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<td>Bimanual</td>
<td>Unimanual</td>
<td>Bimanual</td>
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<td><strong>Wrist marker–shoulder marker</strong></td>
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<tr>
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4.3. Intra-limb coordination in joint-angle space

Similar to effector space, correlations were high in joint-angle space (see Table 3). The coupling between elbow extension and shoulder flexion was higher in the unimanual (0.944) than in the bimanual (0.926) conditions ($F(1, 10) = 7.37, P < 0.05$) and higher for the unimpaired hand (0.962) than the impaired hand (0.908: $F(1, 10) = 31.28, P < 0.001$). In addition, the standard deviation of the correlation coefficient was larger for the impaired hand (0.064) than for the unimpaired hand (0.032: $F(1, 10) = 5.87, P < 0.05$).

Fig. 6. Representative samples of position–position plots of the wrist versus ipsilateral shoulder in the grasping task for one subject. Shown are the unimpaired side in the unimanual (a) and bimanual movement conditions (c), as well as the impaired side ((b): unimanual; (d): bimanual). The arrow indicates the direction of the movement. Printed in the lower left corner of the plot is the average value of the cross-correlation of the samples down.
To indicate the relation between the value of the correlation coefficient and the resulting trajectories in joint-angle space, representative angle–angle plots (elbow extension–shoulder flexion) for one subject during reaching are shown in Fig. 7. Fig. 7(a) and (c) are representative angle–angle plots for the preferred hand in unimanual and bimanual movement conditions, respectively. Fig. 7(b) and (d) show the angle–angle plots of the impaired hand in the unimanual and bimanual conditions, respectively. As was shown in effector space, a lower cross correlation was caused by fragmentation of the movement. For instance, the lowest correlation coefficients (Fig. 7(b) and (d)) clearly show a fragmentation at the start of the movement. The shoulder is flexed first, while the angular change in the elbow joint is minimal. As the

Fig. 7. Representative samples of elbow angle–shoulder flexion angle plots in the reaching task for one subject. Shown are the unimpaired side in the unimanual (a) and bimanual movement conditions (c), as well as the impaired side ((b): unimanual; (d): bimanual). The arrow indicates the direction of the movement. Printed in the lower left corner of the plot is the average value of the cross-correlation of the samples shown.
degree of shoulder flexion reaches approximately 140°, the elbow joint starts to extend. Henceforth, lower values of the correlation coefficient point to a fragmentation of the movement, with the value of the correlation coefficient being a fair indicator of the magnitude of fragmentation.

For the elbow extension–shoulder elevation coupling a similar pattern of results was found. That is, in the unimanual movement conditions a higher coupling strength was found (0.880) compared to bimanual responding (0.826: $F(1, 10) = 12.81, P < 0.01$). Also, there existed a significant difference in correlation coefficient between the unimpaired hand (0.940) and the impaired hand (0.766: $F(1, 10) = 73.36, P < 0.001$). Hence, the decrease in correlation coefficient of the impaired hand was larger (0.766), than was the case for the elbow extension–shoulder flexion coordination (0.908). Finally, the standard deviation of the correlation coefficient was smaller for the unimpaired hand (0.056) in comparison to the impaired hand (0.116: $F(1, 10) = 5.16, P < 0.05$).

Representative elbow extension–shoulder elevation plots are shown in Fig. 8, for the unimpaired arm (Fig. 8(a) unimanual; Fig. 8(c) bimanual) and the impaired hand (Fig. 8(b) unimanual; Fig. 8(d) bimanual). Again, a lower correlation coefficient is concomitant with a more fragmented movement (e.g. Fig. 8(b) and (d)). More specifically, the shoulder is elevated first with little elbow extension, after which elbow extension increases and the shoulder elevation is diminished. In the case of less (or not) fragmented movements (e.g. Fig. 8(a)), increase in shoulder elevation and increase in elbow extension go parallel, thus, are tightly coupled.

4.4. Inter-limb coordination

In this final results section the degree of inter-limb coupling at the level of the end effector during bimanual responding was assessed. As shown before, in the first results section (‘Temporal characteristics...’), movements of both limbs in the bimanual movement conditions displayed a tight temporal invariance at the end of the movement. As an extension, the coupling between both end effectors was determined during the course of the movement. To that aim, within-trial cross-correlations between the resultant velocity profiles of both wrists were calculated. The results of this analysis for both reaching and grasping are shown in Table 3. As can be seen, the values were high pointing to a coupling between both limbs during the ongoing movement. The height of the correlation value was similar for reaching and grasping.
5. Discussion

Understanding the intrinsic dynamics of reaching and grasping movements of subjects with spastic hemiparesis is a necessary prerequisite for the appreciation of abnormal coordination patterns. In the present study, the intrinsic dynamics and conditions that may characterize deviant coordination patterns in subjects with spastic hemiparesis were studied by virtue of an examination of the intra-limb coupling both, in effector space and in joint-angle space. In effector space, the within-trial cross-correlations of the resultant displacement of the wrist and ipsilateral shoulder segments were all very high (means ranging from 0.936 to 0.979; Table 3) suggesting a tight coupling between the two segments under the movement conditions imposed.

Fig. 8. Representative samples of elbow angle–shoulder elevation angle plots in the reaching task for one subject. Shown are the unimpaired side in the unimanual (a) and bimanual movement conditions (c), as well as the impaired side (b): unimanual; (d): bimanual). The arrow indicates the direction of the movement. Printed in the lower left corner of the plot is the average value of the cross-correlation of the samples shown.
In a similar vein, intra-limb coupling in joint-angle space, expressed by the within-trial cross-correlations of the elbow extension–shoulder flexion pair and elbow extension–shoulder elevation pair was high (means ranging from 0.907 to 0.973 and from 0.736 to 0.960, respectively; Table 3). In spite of these apparent high values of the cross-correlation, a consistent finding in the present study was the significant lower value of cross-correlation for the impaired limb, indicating more independent control of the different movement segments. It is important to appreciate what these reduced values exactly mean in terms of coordination between the segments. Figs. 6–8 provide more insight into this matter. As an example, the values of the cross-correlation between elbow extension and shoulder flexion, displayed in Fig. 7, are high for the unimpaired hand (Fig. 7(a) and (c); 0.968 and 0.967, respectively). This results in a fairly straight line in angle–angle space, indicating a strict dependence of the movement from one joint on movement from the other joint, hence, a tight coupling between both joints. In contrast, Fig. 7(b) and (d) show angle–angle paths for the impaired hand for which the values of cross-correlation were also high, but significantly lower compared to the impaired hand (both 0.912). Clearly, the movements of this hand are fragmented. For instance, in the case that the impaired hand moved in isolation (Fig. 7(b)) the movement started with a flexion of the shoulder concurrent with very small elbow extension. Following the point where the angle of shoulder flexion has reached approximately 140°, both joints become coupled in the further course of the movement, as indicated by the straight line (see also Fig. 7(d)). A comparable effect was shown for the coupling between elbow extension and shoulder elevation (Fig. 8(b) and (d)). Initially, the shoulder is elevated with little movement in the elbow joint, after which both joints become more closely coupled. Moreover, Fig. 8(d) shows that a more fragmented movement corresponds with a lower value of the correlation coefficient.

These findings closely resemble those found in the study by Levin (1996). Furthermore, that study showed that movements made to a contralateral target lead to a pronounced fragmentation of the movement in a subject with severe spasticity (see Fig. 2 in that study). Taken collectively, in spite of the fairly high values of cross-correlation between joint pairs in the impaired hand, closer inspection of the trajectories revealed that movements of this hand are considerably fragmented. This fragmentation is caused by the fact that at the start of the movement the shoulder is flexed and elevated followed by an increment in the involvement of the elbow, and a closer coupling between the elbow and shoulder during the remaining course of the movement.
What do these findings tell us about underlying control principles which the CNS may exploit and the essential dimensions along which the recovery of function may take place? Adaptation, or learning depends on the mutual influence of task, environmental and organismic constraints (Newell and McDonald, 1994), the latter being changed dramatically in subjects suffering from cerebral lesion. Subjects in the present study have gone through elaborate rehabilitation programs and it is likely that they have already established a ‘new’ coordination pattern well adapted to their changed neural and motor structures (Hallet et al., 1993). Nevertheless, this coordination pattern was fragmented. It may be presumed that fragmentation of the movement is a manner in which the total set of degrees of freedom of the changed action system is compressed to render control possible (cf. Bernstein, 1967). Comparison of the present findings with those of Levin (1996) may further elucidate this phenomenon. As pointed out in Section 2, subjects in the present study had to be able to reliably grasp the object. This induced a natural selection criterium of the subjects, such that the more severe spastic subjects were not included in the study. In the Levin (1996) study, all subjects suffered from unilateral stroke at a later age, and the onset of stroke varied from 0.5 to 7.2 years. It may well be that the time span between the onset of stroke and the moment of testing was too short for full recovery to take place. Additionally, fragmentation found in that study was larger than found in the present study. Consequently, fragmentation, as operationalised by the value of the cross-correlation between joint pairs is an essential variable by which the level of recovery of function might be captured.

The present results also showed that the impaired limb performed movements with (1) diminished angular change, and (2) increased trunk involvement. This signifies that subjects have ‘learned’ a movement pattern in which the relative contribution of the different segments is changed. In a sense, this new coordinative pattern of trunk and upper-limb involvement may be considered optimal given the altered constraints (cf. Latash and Anson, 1996). The decrease in angular change that was found for the impaired limb may be a direct consequence of an enlarged antagonistic muscle activity, a feature characteristic of spasticity (e.g. Barnes et al., 1994). Generally, spasticity is portrayed as a velocity-dependent increase in tonic reflexes, thus an excessive and awkward activation of skeletal muscles (e.g. Lance, 1980; Barnes et al., 1994). This hypertonia, which is accompanied by an increased resistance to movement, has traditionally been assumed to be due to exaggerated stretch reflexes, but an increasing body of evidence is pointing to
altered passive mechanical properties beginning the main inducements of increased muscle tone (Carr et al., 1995; O’Dwyer and Ada, 1996; for an overview see O’Dwyer et al., 1996). Dietz et al. (1981) for instance, showed that soft tissue changes, i.e. altered mechanical properties of the muscles, are important contributors to hypertonia. As the impaired limb becomes less involved in daily activities, a situation is created that promotes the occurrence of muscle contracture. The muscle is shortened, through the decrease in the amount of sacromeres (e.g. Tabary et al., 1972), and this is accompanied by an increased resistance to passive movement (Tardieu et al., 1982; Bax and Brown, 1985). Taken together these studies show, that adaptive changes in soft tissue, or muscle contracture, are often likely to be responsible for hypertonia, rather than spasticity itself. These altered mechanical properties of the muscles can also explain the present findings of limited change of angular motion in the shoulder (flexion and elevation) and elbow joint.

If the angular motion of the joints is decreased for the impaired limb, then how is the movement goal reached? An increase in trunk involvement was shown in these instances (for a similar finding in hitting movements, see Van Thiel et al., 1997). More specifically, for both body sides the amount of trunk rotation was practically similar. For the impaired side, however, an extra trunk translation on top of the basic rotation movement served to bring the hand close to the target. This finding underscores the necessity to test the movement system in an unconstrained fashion such that the full adaptive behavior can be revealed. Restricting the movements of subjects, as was done in the Levin (1996) study by strapping subjects’ shoulders to the chair, poses an extra control problem for the subjects on top of the already existing control problem. This may even provoke further fragmentation of the movement pattern. The present results unambiguously showed that trunk movement becomes an integral part of the total movement. An analogous trunk involvement has recently been found by Roby-Brami et al. (1997) for the impaired side of hemiparetic subjects in a reaching task, even when the target was well within upper limb reaching range (for similar findings on trunk involvement in subjects without neurological disorders, see Kaminski et al., 1995 and Steenbergen et al., 1995). Kaminski et al. (1995) have shown that the trunk does not solely function as a postural stabiliser during reaching, as was argued by Steenbergen et al. (1995), but becomes an important component in positioning the hand close to the target, of course more so when this target is beyond arm’s length. The latter function of the trunk was also evident for the impaired limb in the present study, notwithstanding the fact that the targets were all within comfortable reaching dis-
tance. Possibly, the decreased involvement of segments distal to the trunk necessitates its function as mover also.

We compared reaching and grasping movements to gain more insight into the role played by both proximal and distal movement components as contributing factors to the movement asymmetry. An ubiquitous feature of spastic hemiparetic subjects is that movements of the impaired limb are performed slower than those of the unimpaired limb (Jung and Dietz, 1975; Sugden and Utley, 1995; Trombly, 1992; Steenbergen et al., 1996; Steenbergen et al., 1998). In this respect, Sahrmann and Norton (1977) found a slow recruitment of the agonist muscles and a delayed termination of agonist contraction during the end of rapid flexion and extension movements at the elbow of spastic subjects (for a similar finding see Tang and Rymer, 1981). The slowness of the impaired limb in the unimanual movement conditions was also a consistent finding in the present study as shown by a decreased mean velocity for this limb. As an extension, we found that the asymmetry in movement performance between both limbs was enlarged during grasping. This was principally due to an increased time spent after zero velocity. It is in this phase, that the hand and fingers are shaped in a proper position for the object and that a stable grip of the object is accomplished before it is lifted. Former research already showed that spastic hemiparetic subjects spent a disproportional long time in contact with the object before it is lifted with the impaired hand compared to the unimpaired hand (Steenbergen et al., 1998). Lack of control to coordinate grip and load force properly (cf. Eliasson et al., 1991, 1992, 1995) lies at the heart of this finding. Subjects in the present study transported the impaired arm close to the target, but needed quite some time before they lifted the object, resulting in an increased asymmetry between both limbs. The basic asymmetry between both limbs that was seen in reaching movements was due to slowness of movement of the proximal musculature. This basic asymmetry was unaltered in the grasping conditions. Nonetheless, if the end of the task (object lift) is regarded, and increased asymmetry between both limbs is seen that is due to distal control problems.

On top of this timing asymmetry, there existed appreciable differences between limbs at the level of the movement quality of the end effector. An increase in the number of zero crossings in the acceleration profile of the impaired hand was found, indicating less fluent movements. Also, time to reach peak velocity dropped significantly for the impaired arm compared to the unimpaired arm. Interestingly, during bimanual conditions, the impaired hand did not change its style of movement organisation in comparison to the unimanual conditions. In contrast, the unimpaired hand ‘mimicked’ the
impaired hand on a number of performance characteristics. In line with earlier findings (Steenbergen et al., 1996), the unimpaired hand adopted the time scale of the impaired hand during bimanual responding (see Fig. 4(a) and (b)). As an extension, analysis of the cross-correlations of the resultant velocity profiles of both end effectors indicate close coupling during the ongoing movement. Also, the kinematic features of the unimpaired end effector closely resembled those of the impaired hand during bimanual responding (see Table 2). The coordination pattern of the impaired hand was evidently stable and the unaltered style of organisation under the impact of the various constraints imposed might imply that the stability of this hand has its toll on the flexibility of behavior. The unimpaired hand, on the other hand, changed its organisational style whenever the imposed constraints demanded such a change. What will be the advantages of this solution for which the stationary states appear to exhibit less dynamic stability? It may be hypothesized that such a system would have greater flexibility in switching from one pattern of coordination to another (Kelso et al., 1988) together with an improved ability to deal effectively with environmental contingencies. Evidence for this has been provided previously by Newell and Van Emmerik (Newell and Van Emmerik, 1989; Van Emmerik and Newell, 1990). In a circle drawing task, the correlations of linear displacements of the wrist, elbow and shoulder were significantly higher in the impaired limb than the unimpaired limb. However, this greater degree of mode-locking was paralleled by a decreased flexibility, as this limb did not change its style of organisation when the scale of the circle diameter was changed. These findings suggest that the greater degree of joint coupling exhibited by the impaired limb is accompanied by a less efficient response to environmental contingencies.

The finding in the present study that the impaired limb did not alter its style of organisation under the impact of the various constraints, whereas the unimpaired limb did, indicates that the unimpaired hand is more flexible in achieving new modes of behavior. Alternatively, the dynamic stability of the impaired limb can only be maintained through compensatory reconfigurations of its intrinsic dynamics, at the cost of flexibility and sensitivity to changing task requirements. Still, a more direct test of this presumed decreased flexibility of the movement pattern of the impaired limb is needed, for instance by introducing a task-switch paradigm (cf. Paulignan et al., 1991). This may also reveal why spastic subjects, despite their apparent stable behavior, have so much difficulty with activities in daily living. Most manual dexterity tests used in clinical settings do not measure task switching behavior but present tasks that are highly predictable. Consequently, the predictive
validity of the test results remains low. Obviously, the tasks in the present study did not directly provoke flexible switching behavior either. In all conditions subjects could reach to a target that was placed comfortably located along their body midline and well within reaching distance. Further research, currently being prepared in this lab, will include a more direct test of flexible switching behavior of the impaired limb. Ultimately, the results of this endeavour will be used to develop an easy-to-use diagnostical procedure for the measurement of upper limb movements in spastic persons.

References


