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The bilateral reach-to-grasp movement of Parkinson's disease subjects

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Summary

The performance of simultaneous movements is said to be disrupted in Parkinson's disease, yet there are some indications that this dysfunction is less evident for bilateral inter-limb actions, as opposed to unilateral simultaneous actions. Focussing specifically upon natural actions, this study uses a three-dimensional kinematic system (ELITE) to assess the movement kinematics of a bilateral non-homologous reach-to-grasp action. The target device consisted of a large cylinder (diameter 8 cm) to which a handle (diameter 0.8 cm) was attached. The task was to reach and grasp the cylinder with one hand (gross grasp) while reaching to grasp the handle with the contra-lateral hand (precision grasp). Overall the results indicated that Parkinson's disease subjects, like controls, showed independent and appropriate kinematic parameterization of each limb. For example, and as a reflection of task precision requirements, the time taken to decelerate upon the item to be grasped was longer for the limb grasping the handle than for the limb grasping the cylinder. Subtle indications of compensatory mechanisms, in response to left upper limb inadequacies of Parkinson's disease subjects, were suggested by findings of an earlier timing of maximum hand grip aperture for the left than for the right hand, and adjustments to the final transport phase of the left arm under bilateral conditions. It is proposed that left–right hand differences are more evident with basal ganglia dysfunction, but that these differences are compensated for by CNS mechanisms so that natural non-homologous reach-to-grasp actions are performed in a functional, coordinated and appropriate manner.

Keywords: bilateral prehension; reach; grasp; Parkinson's disease; laterality

Abbreviation: ANOVA = analysis of variance

Introduction

Many studies of Parkinson's disease subjects have pointed to a dysfunction in the ability to perform two or more movements simultaneously (Schwab *et al*., 1954; Talland, 1963; Talland and Schwab, 1964; Benecke *et al*., 1986; Bennett *et al*., 1993, 1995*a*; Castiello *et al*., 1993*d*, 1994). With respect to bilateral movements performed simultaneously, early works utilized afunctional, experimental tasks. For example, Schwab *et al*. (1954) asked subjects to squeeze a ball with one hand while drawing a triangle with another. Talland and Schwab (1964) required subjects to press a tally counter with one hand while using tweezers to pick up beads with the other hand. The results indicated severe disruption to the movement organization of Parkinson's disease subjects.

Later studies used paradigms which decreased the effects of motor learning and task unfamiliarity. Placing emphasis on speeded responses, Benecke *et al*. (1986) asked Parkinson's disease subjects to flex the elbow of one arm while performing an isometric opposition between the index finger and thumb, with the contralateral arm. Compared with each of these actions performed in isolation, the bilateral action was of slightly longer duration (22–25 ms). Stelmach and Worringham (1988) investigated the performance of bilateral arm pointing movements away from the midline to targets

of varying distance and diameter, and demonstrated that Parkinson's disease subjects showed a similar pattern of performance to controls, i.e. longer reaction times and movement durations under bilateral than under unilateral conditions. A tendency for the limbs to become synchronized in time was explained as reflecting an 'assimilation' effect (Cohen, 1970; Marteniuk *et al.*, 1984).

Overall, these results suggest that Parkinson's disease subjects demonstrate temporal and spatial disruption to bilateral movements when the tasks are artificial and subject to learning effects, but they show co-ordinated coupled movements for tasks which have a potential for common temporal regulation (Stelmach and Worringham, 1988) and which could be classed as reasonably useful.

Kelso *et al*. (1980) used the concept of 'coordinative structure' (Easton, 1972) to explain the inter-limb synchronization that occurs when one limb performs an action which has an index of difficulty that is different from that of the other limb. [Index of difficulty is a measure of the accuracy requirements of the task calculated on the basis of target size and distance (Fitts, 1954).] This concept was formulated from research on bilateral pointing tasks. However, Castiello *et al*. (1993*c*) have shown that this tendency for synchrony was not evident in a natural bilateral reach-to-grasp task. In their study, participants reached to grasp a large cylinder with one hand while reaching to grasp a small pull tab on top of the cylinder (much like the action of reaching to open a can of soft drink). Unlike the results for pointing tasks, and although movement duration was the same for both limbs, movement organization of one limb differed from that of the other and this appropriately reflected the accuracy requirements of each limb. For example, the time spent in homing in upon the target object was longer for the limb reaching to the pull-tab than for the limb grasping the cylinder. The results from this study thus suggested that the nervous system had exerted one mode of temporal constraint (movement duration) but coded appropriately, both in spatial and temporal terms, for the functionally independent actions of precision grip with one hand and whole hand prehension with the other hand.

The differences in movement organization of bilateral reach-to-grasp tasks as opposed to bilateral pointing tasks suggests differences in the manner in which the entire action is coordinated. Using the terminology of Heuer (1985), the coordination of a bilateral reach-to-grasp movement could reflect a shift from a more 'global' neural set, to 'local', limb-specific parameterization. Given the comparative lack of differences between Parkinson's disease and control subjects for bilateral pointing tasks (Stelmach and Worringham, 1988), it could thus be proposed that 'global' coordinative structure is not greatly affected in this disorder. The current study addresses the question of whether or not Parkinson's disease subjects show dysfunction with 'local' independent coding of each limb during a functional bilateral task.

The primary aim is thus to examine the ability of Parkinson's subjects, in early disease stages, to code for independent parameterization when performing an everyday action where one hand reaches to grasp a large cylinder, and the other hand reaches to move a small-diameter lever attached to the cylinder. The choice of two diameters enables the manipulation of difficulty index. The difference in this index should be reflected by independent kinematic parameterization for each arm. Based on many previous kinematic studies of unilateral reach-to-grasp movements (Gentilucci *et al*., 1991; Castiello *et al*., 1992, 1993*b*; Castiello, 1996), and if independent inter-arm parameterization is maintained under bilateral conditions, the higher index of difficulty for the limb reaching to grasp the small-diameter lever should be reflected by a longer deceleration time, for the transport (reach) component, and an earlier peak of maximum grip aperture for the manipulation component, than for the limb reaching to grasp the large diameter cylinder. The study of bilateral prehension can reveal whether the reported dysfunction with simultaneous movement activation in Parkinson's disease applies to functionally and temporally coupled movement components.

Table 1 *Characteristics of the Parkinson's disease (PD) subjects*

PD subject	Age (years)	Sex	Most affected upper limb	Duration of PD diagnosis	Medication	MMSE score
1	55	F	Left	2	Sinemet, Eldepryl	30
2	45	F	Left	3	Sinemet, Eldepryl	30
3	44	F	Right	3	Sinemet, Eldepryl	30
4	51	M	Left	3	Sinemet	29
5	60	M	Left	6	Sinemet, Eldepryl	30
6	39	F	Right	1	Eldepryl	30
7	58	M	Right	7	Sinemet, Eldepryl	29
8	47	M	Right	7	Sinemet, Eldepryl	29
9	39	M	Right	8	Sinemet, Eldepryl	29
10	68	M	Right	1	Sinemet, Eldepryl	30
11	44	M	Left	3	Sinemet	29

All subjects had bilateral signs and symptoms. MMSE = Mini-Mental State Examination (Folstein *et al*., 1975).

Methods

Participants

Of an original volunteer group of 12, 11 Parkinson's disease subjects completed the experiment. The characteristics of these Parkinson's disease subjects are shown in Table 1. The disease was of 1–8 years standing and all subjects were classified at Stage II of the Hoehn and Yahr scale (1967). Medication was most commonly Sinemet and/or Eldepryl. Parkinson's disease subjects were always tested during a period of least signs and symptoms, 1–2 h after medication. None showed motor complications due to therapy, and one Parkinson's disease subject (no. 10) showed a slight bilateral resting tremor. The 11 sex- and age-matched control subjects reported no neurological or skeletomotor dysfunctions. There was no statistical difference in the mean age of Parkinson's disease and control subjects (mean $\pm$ SD = 50 $\pm$ 9.28 and 50.3 $\pm$ 9.2 years, respectively). The Mini-Mental State Examination was used to provide an index of the current global cognitive state (Folstein *et al.*, 1975). The scores of the Parkinson's disease subjects ranged from 29 to 30; all control participants showed a score of 30. A non-parametric comparison (Mann–Whitney *U* test) between Parkinson's disease and control subject scores was not significant. With visual acuity testing, Parkinson's disease subjects scored, on average, 18 out of 20 and control subjects 20 out of 20. All subjects showed right-handed dominance (Edinburgh Inventory; Oldfield, 1971), were naive as to the experimental design or purpose, and gave informed consent to participate. The study was approved by the Standing Committee on Ethics in Research on Humans, Monash University.

Apparatus

Movements were recorded with the Elite system (Ferrigno and Pedotti, 1985). This consisted of two infrared cameras (sampling rate 100 Hz) inclined at an angle of 30° to the vertical and placed 3 m in front of the table and 3 m apart. These cameras were capable of detecting the position of markers placed on the subject's arms. The calibrated working space was a parallelepiped (length 60 cm, breadth 30 cm, height 60 cm) from which the spatial error measured from stationary and moving stimuli was 0.04 mm. Calibration was performed using a grid of 25 markers (5$\times$5), with the centroid of each marker being placed 15 cm from that of another. Using the procedure of Haggard and Wing (1990) the mean length of a bar with two markers attached 15 cm apart, as reconstructed from the ELITE data, was 14.996 $\pm$ 0.002 (SD) cm. Coordinates of the markers were reconstructed with an accuracy of 1/3000 over the field of view and sent to a host computer (PC 486). The standard deviation of the reconstruction error was 1/3000 for the vertical (*y*) axis and 1.4/3000 for the two horizontal (*x* and *z*) axes.

The cylinder/lever target device could be described as resembling a coffee grinder, and is shown in Fig. 1. The cylinder was 8 cm in diameter and 8 cm high. The vertical shaft component of the lever (0.8 cm diameter) was inserted into a hole in the centre of the cylinder, and extended 2 cm above the top level of the cylinder. The horizontal handle component of the lever was 16.7 cm long, with a diameter of 0.8 cm. The shaft rotated in the centre of the cylinder so that the lever could be turned easily by the subject. The handle was positioned pointing to the left when the left arm was required to perform the task of greater difficulty index, and positioned pointing to the right when the right arm performed this task. The cylinder/lever device was placed upon the table, with the centre of the cylinder 34 cm in front of the mid-sagittal point of the table's front edge.

Procedure

The experiment was conducted under normal indoor lighting conditions. The subject was seated in front of the table working surface (1$\times$1 m). Reflective passive markers (0.25 cm diameter) were attached to the following points of each reaching arm: (i) the wrist on the radial aspect of the distal styloid process of the radius; (ii) the index finger on the radial side of the nail; (iii) the thumb on the ulnar side of the nail.

Vertical, pressure-sensitive starting switches were positioned 10 cm to the right and left of the mid-sagittal plane, each 4 cm from the front edge of the table. For bilateral trials, the subject rested the thenar eminence of the right hand on the right switch, and that of the left hand on the left switch. For unilateral trials, only the left or right hand rested against its corresponding switch. Signals were sent from each of these switches to the main computer upon switch release; i.e. upon onset of the respective reaching movement. The starting position for each reaching arm was as follows: shoulder flexion (5°–10°), elbow flexion (90°–100°), forearm mid-pronation, wrist extension (10°–15°), and opposition between the index finger and thumb.

The subject was instructed to commence the reach-to-grasp action upon hearing an acoustic starting signal (880 Hz). For unilateral 'large' trials, the instruction was to grasp the cylinder. For unilateral 'small' trials, the instruction was to rotate the lever; for these trials the cylinder was fastened to the table surface. For bilateral trials, the subject was instructed to grasp the cylinder and move the lever backwards. (Note that data analysis was only of the action up until the point of initially grasping the handle; the movement of moving the lever backwards was not assessed.) No instructions were given as to speed of response, speed of movement, spatial boundaries, or type of grasp to adopt. In addition, subjects were given no explicit instructions about the relative inter-arm timing of contact with the cylinder and handle. By simply observing the two or three practice trials which were conducted prior to each block of trials, and the subsequent experimental trials, it was evident that subjects naturally adopted grasps which were appropriate to the diameter of

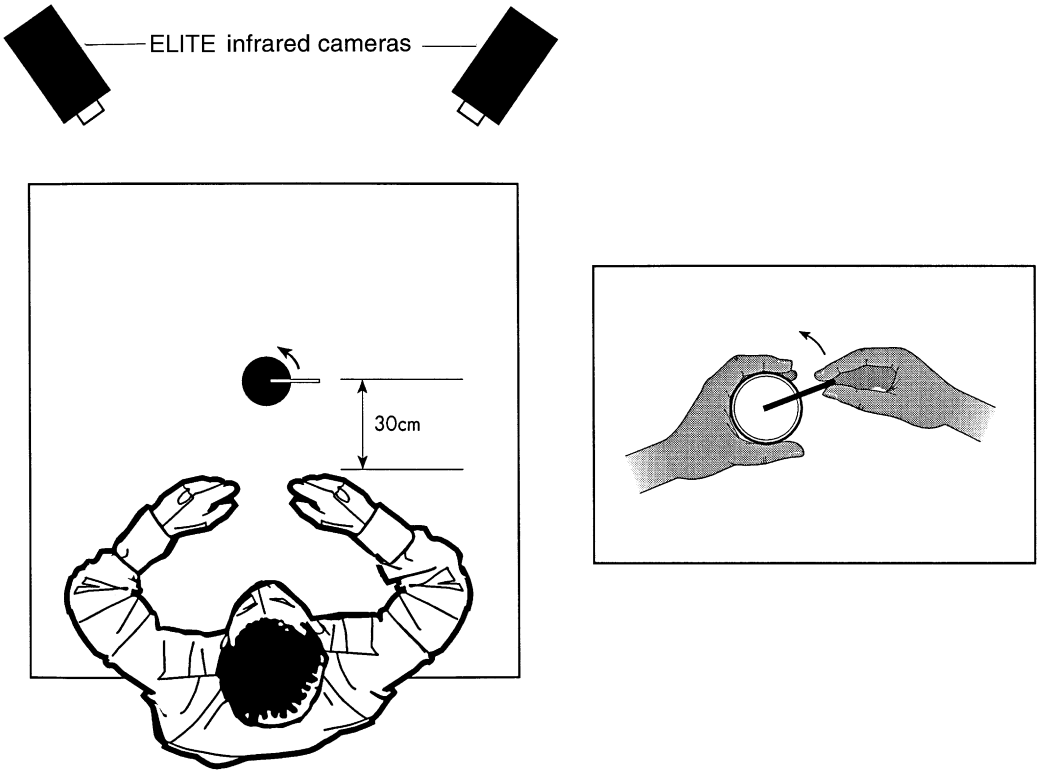

Fig. 1 Experimental set-up. The left view shows the subject seated at the table with the target device positioned directly in front. The ELITE cameras were placed above and in front of the subject for optimal recording of markers positioned upon the wrist and digits of both arms. (Note that the distance between the subject's thorax and the starting position is not to scale.) For the bilateral action, the subject was instructed to grasp the cylinder and move the lever backwards. The right view shows typical grasps adopted for the cylinder (whole hand prehension) and the handle (precision grip).

the device component. The handle was grasped with a precision grip consisting of opposition between the index finger and thumb (Napier, 1956). The cylinder was stabilized with a whole hand prehension characterized by flexion of all the digits around the box and some contact of the cylinder with the palm (see Fig. 1).

Trials were performed in blocks of 10, with the sequence of these blocks being counterbalanced across the original 12 subjects. Unilateral trials consisted of four blocks: the left hand grasping the cylinder or handle, or the right hand grasping the cylinder or handle. Bilateral trials consisted of two blocks: the right hand grasping the cylinder while the left hand grasped the handle, or the left hand grasping the cylinder while the right hand grasped the handle. In the Results section, the cylinder will be referred to as the large object and the handle will be referred to as the small object.

Data processing and analysis

The ELIGRASP (B|T|S, 1994) software package was used to assess the data. This gave a three-dimensional reconstruction of the marker positions. The data were then filtered using a FIR linear filter with a transition band of 1 Hz (sharpening variable = 2; D'Amico and Ferrigno, 1990, 1992). For each arm, the transport component was assessed by analysing the trajectory, velocity and acceleration profiles of the wrist marker. The manipulation component was assessed by analysing the trajectory of each of the digit markers and the distance between these two markers.

Movement initiation time, so-called because no emphasis was placed on a speeded response, was taken from release of the starting switch. Onset of the manipulation component was taken as the time at which the hand began to open; i.e. when the distance between the index finger and thumb markers was no longer constant and showed increments >0.04 mm. The end of the action was taken as the time when the fingers closed upon the object and there was no further change in the distance between the index finger and thumb of either hand. Movement duration was taken as the time between movement onset and the end of the action. The period following this, whereby the lever was turned, was not assessed. To allow for the well-known slowing of movements in Parkinson's disease subjects, absolute temporal values obtained from both subject groups were expressed as a percentage of movement duration (e.g. the absolute time at which peak velocity occurred was expressed as a percentage of movement duration). Throughout the results, these are referred to as relative values.

For the purposes of description, the dependent variables can be divided into three groups: (i) initiation time and

movement duration; (ii) transport component parameters (time and amplitude of peak velocity, time and amplitude of peak acceleration, time and amplitude of peak deceleration of the wrist marker and the number of submovements); (iii) manipulation component parameters (onset time of manipulation, and time and amplitude of peak grip aperture). For each dependent variable (and its relative value where appropriate) an analysis of variance (ANOVA) was performed with group (Parkinson's disease, control) as a between-subjects factor and type of task (unilateral, bilateral), size of object (small, large) and hand (right, left) as within-subjects factors. In order to test variability for all dependent measures, analyses with the same structure were conducted on the SDs. *Post hoc* comparisons were conducted on the means of interest using the Newman–Keuls procedure.

For bilateral conditions, bivariate correlation coefficients were calculated between temporal parameters measured from one arm and the corresponding parameters of the contralateral arm. The following parameters were included in this analysis: (i) time to peak acceleration; (ii) time to peak velocity; (iii) time to peak deceleration; (iv) time to maximum grip aperture. For each subject, a correlation coefficient was determined for all ten trials of each condition. Hence, a coefficient was determined between the time of peak acceleration for the left arm and the time of peak acceleration for the right arm, for both types of bilateral trials. The Fisher-*Z* transformation of data was used for homogeneity of variance and to counteract any non-normal distributions. The significance of each correlation was assessed with Student's *t* test

Results

Similarities between Parkinson's disease and control subjects

Probably the most striking finding of this study was the similarity of performance between the two groups. Despite a greater incidence of submovements for the Parkinson's disease group (*see* Differences between Parkinson's disease and control subjects section), the relative temporal organization of the transport component of both unilateral and bilateral movements were similar across the two groups. For example, peak acceleration of the bilateral movement occurred at 30.5% of movement duration for Parkinson's disease subjects, and at 29.5% for control subjects. Deceleration time lasted for 52.5% of movement duration for Parkinson's disease subjects, and 54% for control subjects. In other words, both the acceleration and deceleration parts of bilateral movements appeared to be appropriately organized at a global temporal level for Parkinson's disease subjects. Table 2 presents the relative values of parameters measured from the transport component; there were no group effects for the ANOVAs of these measures.

A common means of assessing whether or not motor performance is affected in neurological disorders is to evaluate movement patterning under a variety of comparative conditions. In such an evaluation, the following questions are likely to be included. Will the difference between unilateral and bilateral movements be the same in the brain-damaged subject group as the control group? Will the difference between movements involving a small object and those involving a large object be similar across the two groups? Will differences between the left and right hand be the same for both groups? Such an analysis assists in dissociating those differences that are due to the slowness observed in Parkinson's disease from those that are due to dysfunctions in motor planning.

Table 2 *Temporal parameters measured from the wrist markers of the left and right reaching arms of the Parkinson's disease (PD) and control subjects*

	Left hand		Right hand	
	PD subjects	Controls	PD subjects	Controls
Unilateral movements (%time)				
to peak acceleration	30 ± 4	29 ± 3	29 ± 4	26 ± 3
to peak velocity	46 ± 5	46 ± 5	45.5 ± 4	44 ± 5
to peak deceleration	62 ± 6	63 ± 5	61 ± 6	61 ± 6
for deceleration	54 ± 5	54 ± 5	54.5 ± 4	56 ± 5
Bilateral movements (%time)				
to peak acceleration	32 ± 4	29 ± 5	31 ± 3	28 ± 3
to peak velocity	47 ± 5	48 ± 5	47 ± 4	45 ± 4
to peak deceleration	61.5 ± 6	64 ± 6	62 ± 6	61 ± 6
for deceleration	53 ± 5	52 ± 4	53 ± 5	55 ± 5

Data (mean ± SD) are expressed as a percentage of the total movement duration. This normalization was performed for comparative purposes, because PD subjects show slower, longer duration movements than control subjects. Note that data concerning different object sizes are pooled. There were no group effects for the ANOVAs performed on the dependent measures in this table.

Table 3 shows the results when comparing the unilateral and bilateral conditions. This table gives the significant main effects for type of task (unilateral, bilateral) and illustrates that the patterning of movement for the Parkinson's disease subjects is similar to that of control subjects (i.e. absence of group by type of task effects). The main result from this comparison is that both groups show a generally slower movement for bilateral actions. Further, the greater variability of some parameters suggests that the processing demands of the bilateral task are greater for both groups.

Many previous studies have demonstrated that the kinematics of the reach-to-grasp movement change according to the size of the object to be grasped (Marteniuk *et al*., 1990; Gentilucci *et al*., 1991; Castiello *et al*., 1992, 1993*b*, *c*), and this was confirmed for both groups of the current study for the non-homologous bilateral task. The results for both the transport (reach) and manipulation components are shown in Table 4. Figure 2 illustrates this size effect for the relative temporal parameter of deceleration time (a transport component parameter). From this figure it can be seen that the time spent in homing in upon the target is greater when the target requires more precision, and

Table 3 *A comparison of the results from the bilateral and unilateral conditions*

	Bilateral	Unilateral	*F* value
Movement initation time (ms)	469 ± 59	415 ± 56	$F(1,20) = 28.63$, $P < 0.0005$
Movement duration (ms)	1253 ± 109	1144 ± 124	$F(1,20) = 16.08$, $P < 0.001$
Peak acceleration (mm/s^2)	2020 ± 505	2371 ± 487	$F(1,20) = 9.99$, $P < 0.005$
Peak velocity (mm/s)	598 ± 68	649 ± 72	$F(1,20) = 14.14$, $P < 0.001$
Peak deceleration (mm/s^2)	1663 ± 371	1853 ± 404	$F(1,20) = 4.41$, $P < 0.05$
SD of 'time to peak velocity' (ms)	77 ± 4	64 ± 5	$F(1,20) = 11.10$, $P < 0.005$
SD of 'time to peak deceleration' (ms)	97 ± 9	85 ± 8	$F(1,20) = 4.72$, $P < 0.05$

Data (mean ± SD) are pooled for group, size and hand. The last two rows show the analyses of the SDs of the means of two transport-component parameters. These results indicate that bilateral movements are generally slower than unilateral movements, and that the processing demands of the former may be greater.

Table 4 *A comparison of movements to the handle (Small) with those to the cylinder (Large) during bilateral trials*

	Small	Large	*F* value (main effect size of object)
Movement duration (ms)	1250 ± 128	1147 ± 114	$F(1,20) = 23.05$, $P < 0.0005$
Transport component			
Time to peak acceleration (%)	28 ± 5	30 ± 4	$F(1,20) = 24.97$, $P < 0.0005$
Time to peak velocity (%)	43 ± 6	48 ± 4	$F(1,20) = 37.77$, $P < 0.0005$
Time to peak deceleration (%)	59 ± 6	65 ± 6	$F(1,20) = 29.56$, $P < 0.0005$
Deceleration time (%)	56 ± 7	51 ± 5	$F(1,20) = 37.64$, $P < 0.0005$
Peak acceleration (mm/s^2)	2091 ± 399	2300 ± 345	$F(1,20) = 17.68$, $P < 0.0005$
Peak velocity (mm/s)	597 ± 73	649 ± 44	$F(1,20) = 48.64$, $P < 0.0005$
Peak deceleration (mm/s^2)	1685 ± 218	1830 ± 176	$F(1,20) = 7.83$, $P < 0.01$
Manipulation component			
Time to maximum grip aperture (ms)	64 ± 8	68 ± 6	$F(1,20) = 20.37$, $P < 0.0005$
Maximum grip aperture (mm)	44 ± 6	94 ± 9	$F(1,20) = 397.89$, $P < 0.0005$

Data (mean ± SD) is pooled for group and hand. Movements to the small object are longer with an extended deceleration phase.

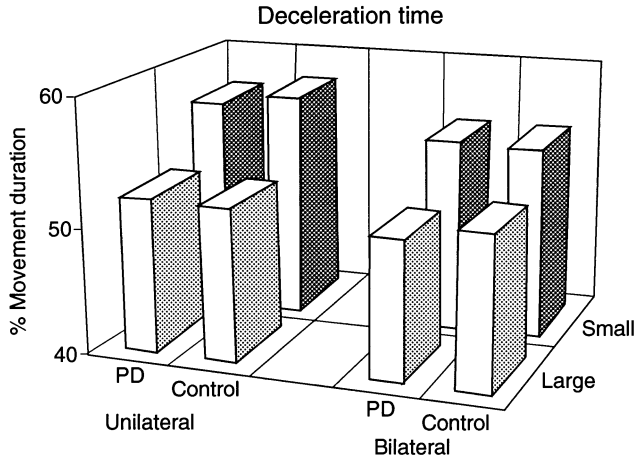

Fig. 2 The pattern of results for the parameter of 'Deceleration time' according to target object size. Both groups show longer deceleration phases when reaching to grasp the small object than when reaching to grasp the large object. Deceleration time refers to the phase from peak arm velocity to the end of the movement (grasp of device). Mean relative values (absolute deceleration time expressed as a percentage of movement duration) for each group are illustrated. PD = Parkinson's disease subjects; Control = control subjects; Large = cylinder target; Small = handle target; Unilateral = one limb reaching to grasp one part of the device; Bilateral = one limb reaching to grasp the cylinder while the contralateral limb reaches to grasp the handle.

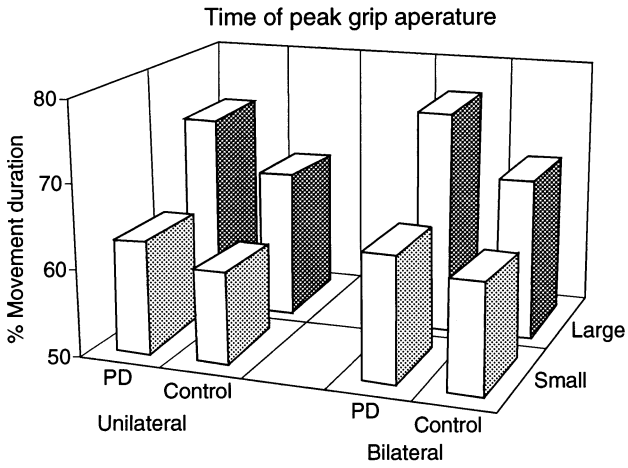

Fig. 3 The pattern of results for the parameter of 'Time of peak grip aperture' according to target object size. This parameter is the time after movement onset that the hand reaches maximum aperture between the index finger and thumb. It is determined by calculating the distance between markers on the distal aspects of these digits. Both groups show earlier settings of this parameter when reaching to grasp the small object than when reaching to grasp the large object. Please refer to the legend of Fig. 2 for further explanation of this figure.

Table 5 *Left–right correlations for temporal parameters of the upper limbs during bilateral movements*

Temporal parameter	PD subjects		Controls	
	Coefficient	Significant (*n*)	Coefficient	Significant (*n*)
Right hand to the cylinder and left hand to the handle				
Peak acceleration	−0.77 to +0.39	0	−0.64 to +0.46	0
Peak velocity	−0.24 to +0.4	0	−0.52 to +0.72	1
Peak deceleration	−0.76 to +0.35	0	−0.37 to +0.76	2
Peak grip aperture	−0.29 to +0.82	2	−0.77 to +0.84	1
Right hand to the handle and left to the cylinder				
Peak acceleration	−0.76 to +0.69	1	−0.43 to +0.97	1
Peak velocity	−0.56 to +0.59	0	−0.83 to +0.96	1
Peak deceleration	−0.42 to +0.87	1	−0.89 to +0.86	1
Peak grip aperture	−0.52 to +0.87	2	−0.71 to +0.95	2

Significant (*n*) = number of significant correlations ($P < 0.05$) from the 11 PD subjects.

that each arm shows individual parameterization during bilateral actions.

Figure 3 shows this size effect for the relative temporal parameter of peak grip aperture (a manipulation component parameter). It can be seen that the time at which the hand reaches its maximum aperture during the reaching movement is relatively earlier for the handle (small diameter) than for the cylinder (large diameter). Similarities between the two groups extended even to the finding for some parameters, but only under the bilateral condition, that the left hand did not follow the size rule. Specifically, movement duration of the left arm was not greater for the small (1232 ms) than for the large object (1241 ms) during bilateral actions ($F(1,20) = 5.52$, $P < 0.02$). Further, the pattern of variability was generally the same for both groups with greater variability for the small than for the large object, and greater variability for the left than for the right hand.

In summary, movement parameterization for both groups reflected the different object precision requirements afforded by large and small objects, with each arm showing an individual pattern of movement even with bilateral actions. There was also evidence that despite the individual movement parameterization of each arm, the patterning of one arm could influence that of the other. As an example, both Parkinson's disease subjects and controls demonstrated a lower large–small difference in the timing of peak grip aperture for bilateral than for unilateral tasks [interaction between type of task and object size: $F(1,20) = 5.96$, $P < 0.05$; bilateral time difference (large – small) = 893.5 – 790.5 = 103 ms and unilateral time difference (large – small) = 831 – 672 = 159 ms; $P < 0.05$].

Results obtained from the correlational analyses supported the findings of similarities between the two groups, and confirmed the general findings of inter-arm temporal independence for non-homologous bilateral tasks. To summarize, and in concordance with the results of Castiello *et al*. (1993*c*), the parameters of the left arm showed no general pattern of co-ordination with those of the right arm. These results are shown in Table 5.

Differences between Parkinson's disease and control subjects

The most obvious difference between Parkinson's disease and control subjects was the greater incidence of submovements during the deceleration phase of the reaching movement. A submovement can be defined as an obvious increase in velocity during the period in which the velocity is generally decreasing from its maximum. Figure 4 shows nine examples of submovements identified on the velocity profile of a left arm bilateral reaching action performed by a Parkinson's disease subject.

Only two control subjects showed one or two submovements (considering all trials of these two subjects, the mean was 1.1). All Parkinson's disease subjects showed submovements (mean 3.56), and this was particularly marked for the left hand under the bilateral condition. There was no relationship between the presence of submovements and greater signs and symptoms in the left arm. The pattern of submovements for the one subject who showed visible tremor was no different from that of those subjects who showed no visible tremor; the resting tremor was evident from small peaks in the velocity prior to movement onset. Despite the occasional presence of quite a number of submovements, the proportional organization of the movement for Parkinson's disease subjects was similar to that for control subjects. The relative amount of time in the acceleration and deceleration phases was not affected by the presence of submovements.

Subtle but inconsistent indications of further between-group differences were revealed for some transport-component parameters with the analysis of variability. For example, under the bilateral condition, time to peak acceleration for the left hand of Parkinson's disease subjects was more variable than that of the right hand (91 ms versus 77 ms, $P < 0.05$) and more variable than that of control subjects [interactions between group, type of task and hand $F(1,20) = 6.68$, $P < 0.05$). Overall, the results from this analysis suggested that the left arm of Parkinson's disease subjects during bilateral actions was subject to a greater degree of variability in absolute terms. However, no

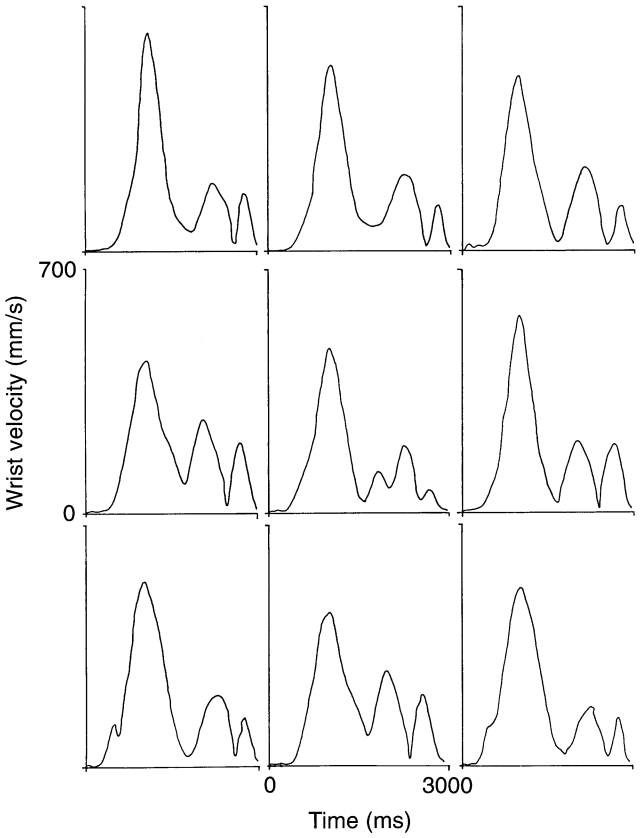

Fig. 4 Left wrist marker velocity profiles showing examples of submovements during the deceleration phase of a bilateral movement (Parkinson's disease subject 3). Nine different movements of the left arm reaching to grasp the handle are illustrated. (The right arm results, reaching to grasp the cylinder in the same bilateral action are not illustrated.) The abscissa (common for all plots) begins at time zero (movement onset) and extends to 3000 ms after movement onset (at which point the small-diameter handle was grasped). The ordinate axis ranges from zero velocity to 700 mm/s for all nine plots. Maximum velocity is the highest peak in each plot. The small peaks which follow indicate submovements, i.e. further slight increases in velocity during the deceleration phase of movement. This figure demonstrates that the majority of left-hand trials performed by this Parkinson's disease subject show two submovements.

increase of variability was found for the relative value of each parameter.

Assessment of the manipulation component revealed particular dysfunctions for Parkinson's disease subjects with the inter-arm parameterizaton of the left and right hands. The time at which the left hand of Parkinson's disease subjects began to open (mean = 4.8% of movement duration), i.e. onset of the manipulation component, was consistently later than the time at which the arm began the reaching action [interaction between group and hand, $F(1,20) = 5.88$, $P < 0.05$ $P_s < 0.05$). This contrasted with the right-hand results for Parkinson's disease subjects (1.4%) and with the results for both hands of the control subjects (–4.2% and –2.7%, respectively), and was observed for both unilateral and bilateral conditions. Indications of effects upon the later phases of the manipulation component were provided with the analysis of peak grip-aperture, i.e. the point of maximum aperture between the index finger and thumb. The relative timing of peak grip-aperture was earlier for left hand movements of Parkinson's disease subjects than for right hand movements [interaction between group and hand, $F(1,20) = 7.83$, $P < 0.01$, 63% versus 69%], and as illustrated in Fig. 5, this difference between the hands was particularly marked for bilateral actions [interaction between group, type of trial and hand $F(1,20) = 6.62$, $P < 0.01$]. For the parameter of grip aperture, Parkinson's disease subjects generally showed a lower maximum grip aperture than control subjects [main effect for group $F(1,20) = 6.0$, $P < 0.05$, 65 versus 74 mm, respectively].

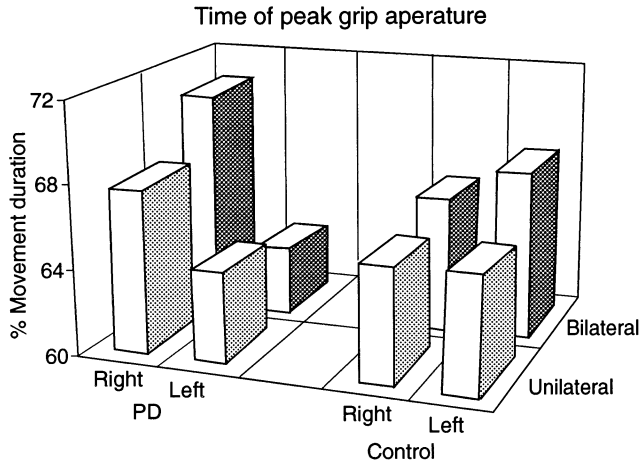

Fig. 5 The pattern of results for the parameter of 'Time of peak grip aperture' according to hand utilized. For Parkinson's disease subjects, the timing of this parameter was earlier for the left than for the right hand, particularly under bilateral conditions. Please refer to the legend of Fig. 2 for further explanation of this figure.

Discussion

Many experimental paradigms employed in the study of inter-limb co-ordination could be criticized for biasing performance to support theories of internal oscillator generators with common temporal control mechanisms (Easton, 1972; Von Holst, 1973; Kelso *et al.*, 1980; Kugler *et al.*, 1980; Marteniuk *et al.*, 1984). However, most bilateral primate actions require asymmetry and limb independence together with cooperative inter-limb goal-directed coordination. For those who favour the idea of co-ordinative structures, inter-limb independence has been explained as representing a suppression of strong tendencies towards synchronization, the latter being the easiest and most readily chosen organizational option of the neural system. Taking this line of argument to an extreme this would imply that most everyday bilateral actions do not use easily flowing and available mechanisms for limb independence, but involve a battle to suppress the underlying forces which drive continuously for inter-limb coupling.

The results from the current study add further fuel to the question of how the neural system operates under bilateral conditions, and what function is played by the basal ganglia in this operation. The paradigmatic emphasis in this study was twofold: (i) the task was natural, and thus the experiment was largely free of learning effect confounds; (ii) the task incorporated aspects of previous bilateral studies which manipulated the index of task difficulty for each limb, thus allowing some degree of comparison with previous studies. The Parkinson's disease subjects of this study (all at an early disease stage) showed minimal dysfunction in the ability to recruit and execute motor patterns which are individual to each limb. The action was performed without error, and without the complete breakdown of spatiotemporal organization which has been reported by earlier investigators for very experimental tasks. Parkinson's disease subjects did not over- or undershoot the targets, nor use inappropriate grasps. They demonstrated no visible difficulty in performing bilateral actions with which they were presumably familiar and practised.

The detailed three-dimensional kinematic assessment shows that Parkinson's disease subjects, notwithstanding their slowness of movement, show patterns of movement organization which are very similar to that of control subjects. Above all they demonstrate independent limb parameterization according to object size, and this independence is evident for the transport (reach) and manipulation (grasp) components of both limbs. Thus, for movement to the handle (small diameter), the acceleration phase is shortened, and the deceleration phase lengthened. This lengthening of the 'homing-in' phase with increased precision requirements reflects time used for visuokinaesthetic feedback and to code for independent use of the index finger and thumb (Marteniuk *et al*., 1990; Gentilucci *et al*., 1991; Castiello *et al*., 1992, 1993*b*, *c*). Similarly for the manipulation component, Parkinson's disease subjects, like controls, show a smaller amplitude and earlier maximum grip-aperture for the limb that reaches to grasp the handle than for the limb that reaches to grasp the cylinder. (Note: the generally lower amplitudes of grip aperture for the Parkinson's disease subjects probably reflects biomechanical differences stemming from muscle rigidity.) Such a result pattern indicates that coding for movement parameterization includes consideration of the intrinsic object characteristics (Jeannerod, 1984), and that this coding is independent to each limb and appropriate for the task required of each limb.

Using the ideas of 'coordinative structure' theory, it could be postulated that a brain-damaged subject may seek easier solutions to the problem of binding the two limbs for a co-ordinated action, and that they may be less able to suppress the natural tendency for temporal synchronization [e.g. as has been reported for split brain and genetic acallosal subjects (Preilowski, 1972; Jeeves *et al*., 1988; Tuller and Kelso, 1989)]. One means of doing this would be to maintain limb independence but within certain temporal constraints. An example of one constraint could be movement duration, a likely candidate, given the results of inter-limb equivalence for this parameter in the previous study of non-brain-damaged subjects by Castiello *et al*. (1993*c*). However, a notable difference from the results of this latter study, is the finding of inter-limb differences in movement duration for both control and Parkinson's disease subjects of the current study. Although this is undoubtedly due to object-related differences [e.g. the centre of both targets in that Castiello *et al*. study coincided, whereas the small target (handle) in the current study was 16.7 cm lateral to the centre of the large target (cylinder)], the similarity of results across the two groups in this current study, suggests that Parkinson's disease subjects do not show a greater tendency for temporal synchronicity under conditions which demand greater independence.

As an example of another 'temporal constraint', it might be expected that compensation for neural damage would include a system of joint programming which enhances the correlation between key kinematic parameters of each limb. However, no evidence for an increase of co-ordination is found with correlational analysis, the limbs being unified at a functional level with a loose degree of temporal coupling. This concurs with the results obtained from non-brain-damaged subjects of no defined correlation pattern for non-homologous reach-to-grasp actions (Castiello *et al*., 1993*c*; Marteniuk *et al*., 1984).

Differences between control and Parkinson's disease subjects emerge when comparing movements of the left and right limbs. For bilateral Parkinson's disease hand actions, there was a tendency for sequencing, with the left hand reaching peak opening prior to the right hand. This could reflect left–right interactions in right-handers; functionally the left hand acts often in a stabilizing manner while the right hand performs precision type tasks (Peters, 1994). From this, it could be predicted that Parkinson's disease subjects might show greater difficulties under conditions where these roles are reversed. However, anticipation of left hand opening is characteristic of bilateral reach-to-grasp movements to both large (cylinder) and small (handle) objects.

The earlier left grip aperture may indicate a means by which neural pathways compensate for basal ganglia damage, and the consequent inadequacies in left hand performance under bilateral conditions. It is known, for example, that the left hand is more forceful and variable than the right hand (Todor and Kyprie, 1980) and, as also shown by results from the current study for both groups, that kinematic parameterization of the left hand differs from, and is more variable than, that of the right hand under bilateral conditions (*see* also Marteniuk *et al*, 1984). There are some suggestions from the current study that the left–right hand differences may be even more exaggerated in Parkinson's disease. For example, under both bilateral and unilateral conditions, it was only the left hand of this subject group that showed a delay in manipulation-component onset with respect to onset time of the transport component. Compensation mechanisms to the timing of grip aperture may thus operate to allow for

limitations in left hand performance so that an adequate task-related performance is maintained.

The patterning of submovements suggests that these transport-component adjustments also reflect compensatory mechanisms (*see* also Warabi *et al*., 1988; Castiello and Bennett, 1994). Despite the presence of one or more submovements, the relative proportion of the deceleration phase is not increased, and its duration maintains a negative relationship with object size. Such proportional and task-related results would not be expected if Parkinson's disease subjects were placing greater emphasis on visual feedback to guide the final stages of the movement (*see* Cooke *et al*., 1978; Stern *et al*., 1983; Flash *et al*., 1992). In this latter case, the expectation would be for a prolonged deceleration phase in both absolute and relative terms. Further support for the pre-programming notion, rather than a dependence upon visual feedback, comes from previous studies that have demonstrated the presence of submovements even in the absence of vision (Meyer *et al*., 1988, 1990; Castiello *et al*., 1993*a*). It is thus proposed that the presence of submovements is an additional compensation mechanism for limitations in left-hand performance.

Problems encountered by Parkinson's disease subjects in the shifting and allocation of attention (Sharpe 1990; Wright *et al*., 1990; Yamada *et al*., 1990; Bennett *et al*., 1995*b*; Mari *et al*., 1997), particularly in three-dimensional space (Bennett and Castiello, 1996), could explain the limitations of left upper limb performance in a bilateral task. According to Peters (1990), attention is directed briefly and intermittently to the left hand of right-handers who are not brain-damaged, while being focussed largely upon the right hand. It is thus feasible that difficulties in transferring attention quickly to and from the left hand, or in splitting attention differentially, could affect the temporal and spatial motor patterning of the left hand, necessitating the use of compensatory strategies.

What does this study reveal about the role of the basal ganglia in the control of bilateral upper limb movements? As implied throughout this text, the answer can be determined only through due consideration to task characteristics, and it is probable that the task employed in this study lies somewhere at the threshold between determining normality and abnormality. The reason for suggesting a threshold effect is that the differences between Parkinson's disease and control subjects do not disrupt the patterning of the bilateral action, but are nevertheless present. It can be suggested that it is the addition of a grasping action that has promoted the revelation of these subtle effects, because no great differences of patterning were found by Stelmach and Worringham (1988) in a pointing task where the emphasis was clearly on transport component mechanisms alone. However, they only assessed reaction time and movement duration.

At the neuroanatomical level, the addition of the grasp component means the employment of centres/pathways which have a more of an independent unilateral nature than the centres/pathways underlying reaching. For example, inter-hemispheric callosal connections between homologous areas of the sensory and motor cortices are minimal for those areas which code for hand musculature (Pandya *et al*., 1969; Rouiller *et al*., 1994). The lateral corticospinal system projects largely to the contralateral motoneuron pools of distal upper limb muscles which would be utilized in grasping actions (Kuypers, 1964; for review, *see* Bennett, 1991), while the more proximal muscles employed in reaching (pointing) actions are subserved by cortical and brainstem pathways which project to both sides of the spinal cord (Kuypers and Brinkman, 1970). Grasping, whether it is of a gross or precise nature, would thus require activation of pathways which have quite a high degree of inter-hemispheric anatomical autonomy. Given the subtle differences between Parkinson's disease and control subjects in this study, it could be proposed that activation of anatomically independent pathways by both upper limbs may increase the likelihood of basal ganglia involvement. With this involvement comes the activation of motor circuit loops which are somatotopically and functionally specific (Alexander *et al*., 1986; Parent, 1990), such that the neural pathways operating for the grasp component are probably largely distinct from those operating for the transport component (Bennett *et al*., 1995). Addition of the grasp component to the task thus also means the recruitment of anatomically independent pathways within each hemisphere.

Abnormalities of basal ganglia function are most probably expressed at the level of the supplementary motor area. During a non-homologous bilateral action, each supplementary motor area is thought to influence activity in the ipsilateral motor cortex while exerting a controlling influence over the contralateral supplementary motor area (Goldberg, 1985). Given its large input to the supplementary motor area, the basal ganglia are well placed to influence the balance of this inter-hemispheric crosstalk. The current results suggest a slight tendency towards sequentialization with damage to basal ganglia. However, evidence of compensatory mechanisms would suggest that abnormal input from both basal ganglias is taken into account by the supplementary motor areas during determination of the essential spatio-temporal characteristics of a non-homologous bilateral reach-to-grasp action.

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