The co-ordination and phasing of a bilateral prehension task
The influence of Parkinson’s disease

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Summary
Parkinson’s disease patients and control subjects performed a simultaneous bilateral reach-to-grasp task to two different sized objects and then pulled the two objects apart. The first phase of the task (reaching-to-grasp) allowed us to examine the issue that impairments in simultaneous movements for Parkinson’s disease patients are seen in some tasks but not in others. It is suggested that the reason for this selective impairment is that Parkinson’s disease compromises the ability to control multiple task-level degrees of freedom independently and concurrently (task-level degrees of freedom are defined as the number of independent parameters that require specification to perform the task). The first phase was used to test the hypothesis that Parkinson’s disease results in a reduction of degrees of freedom that are independently controlled. It was predicted that Parkinson’s disease patients would produce similar (homologous) movements of the two limbs (a symmetrical pattern) if the target objects have different accuracy requirements when they reach bilaterally to the two objects. For bilateral reaches for two different-size objects, only the control group showed reliably different patterns in the two limbs (asymmetrical pattern), while the Parkinson’s disease group displayed a symmetrical pattern. These results provide support for the hypothesis that Parkinson’s disease patients have a reduced capability to control multiple task-level degrees of freedom. The second phase of the task, which involved a transition from position control (reaching-to-grasp) to force control (stabilizing and pulling) was used to examine the ability of Parkinson’s disease patients to make transitions between movement tasks and force control. In contrast to control subjects, Parkinson’s disease patients produced staircase patterns for grip and load forces. Furthermore, a breakdown in the parallel coordination between grip and load force was observed for Parkinson’s disease patients. These data suggest that Parkinson’s disease disrupts the normal feedforward operations responsible for the co-ordination between grip and load forces.

Keywords: bilateral prehension; Parkinson’s disease; grip force; degrees of freedom

Abbreviations: IRED = infra-red emitting diode; SMA = supplementary motor area

Introduction
There are many studies reporting that Parkinson’s disease patients experience particular difficulties executing two upper limb tasks simultaneously, either when the tasks are performed by different limbs (Schwab et al., 1954; Talland and Schwab, 1964; Weiss et al., 1997) or simultaneously by the same limb (Benecke et al., 1986; Phillips et al., 1989). A common real-world example of the latter type is the reaching-to-grasp action which provides a useful model for studying concurrent motor task execution in Parkinson’s disease (Müller and Stelmach, 1992; Castiello et al., 1993a), especially since a majority of Parkinson’s disease patients complain of having difficulties with manipulative tasks, often expressed as having ‘clumsy hands’ (Jankovic, 1987).

Results from our laboratory strongly suggest that, despite significant non-specific impairments of movement execution (bradykinesia, lack of smoothness, hypometria and difficulties controlling movement speed), the basic pattern of concurrent execution of the transport and grasp components of the reach-to-grasp action is unaffected by Parkinson’s disease (Müller and Stelmach, 1992; Saling et al., 1996; Tresilian et al., 1997). This is consistent with the view that established motor programmes are intact in Parkinson’s disease, though
problems arise in executing them, i.e. there are problems of initiation and of execution by a motor system impaired by rigidity and tremor (Marsden, 1982; Bloxham et al., 1984; Stelmach et al., 1986; Weiss and Stelmach, 1997).

If this view is correct, it might be expected that increasing the execution demands of a task would present a Parkinson’s disease patient with problems and result in an exacerbation of non-specific movement deficits and/or a disruption of co-ordination. We have recently investigated this question using reach-to-grasp tasks. Execution demands were increased using two manipulations: first, the number of joint/muscle-level degrees of freedom which needed to be controlled for effective performance of the task was increased. It has been found in manual drawing tasks that Parkinson’s disease patients have difficulty co-ordinating multiple degrees of freedom (Teulings et al., 1997). Secondly, the requirements for accurate digit pad placement were systematically varied by changing the grasp surface area (precise pad placement is more demanding). In two recent experiments (Tresilian et al., 1997; Saling et al., 1996) we examined the effects of these manipulations. In the first, joint level degrees of freedom were increased from the five to seven used in the standard unimanual prehension task (Jeanerod, 1984; Wing et al., 1986; Wallace and Weeks, 1988; Marteniuk et al., 1990; Jakobsen and Goodale, 1991; Castiello et al., 1993a) to 10 to 12 by using a bilateral task in which the object is grasped by opposing the index fingers of the two hands (Tresilian et al., 1997). Detailed individual subject analyses demonstrated that the Parkinson’s disease patients were not differentially impaired by the increased number of degrees of freedom and the increase in the number of degrees of freedom did not interact with increases in accuracy constraints. A similar finding was obtained in the second experiment. In this study, subjects reached to grasp an object which was placed such that leaning forward with the upper body was required to grasp it (Saling et al., 1996). Adding this additional component, or degree of freedom, presented no problems for the Parkinson’s disease patients who were not differentially impaired in this task; their co-ordination of trunk and arm movements was similar to that of control subjects.

The experiment reported here extends these studies to the case in which two unimanual reach-to-grasp tasks are executed simultaneously. A task of this kind was first studied in the healthy population by Castiello et al. (1993b) who examined the movement kinematics of subjects who reached simultaneously for a large cylinder with one hand and a small pull-tab attached to the top of the cylinder with the other hand. It was found that the two reaches were executed simultaneously with almost identical movement times for the two limbs, but the movement kinematics were adapted to the particular characteristics of the object being reached for; Castiello and Stelmach (1994) reported similar results. Related results have been reported in pointing tasks; although the movement times of the two limbs are the same (Kelso et al., 1979), the detailed kinematics of each limb depend upon the accuracy constraints imposed on the pointing movement (Marteniuk et al., 1984).

The bilateral reach-to-grasp task studied by Castiello and Stelmach (1994) in the healthy population involves the concurrent co-ordination of multiple degrees of freedom in four component sub-tasks (the transport and grasp components of the two reaches) which are independently adapted and controlled so as to be appropriate for different target objects in different positions. Thus there are both many effector system (joint/muscle) degrees of freedom and many task-level degrees of freedom involved in performance. ‘Task-level degrees of freedom’ is defined to mean the number of parameters that require specification in order to perform the task, irrespective of the effectors that are actually used for performance. For example, a typical reach-to-grasp task requires that the grasping effectors (e.g. finger and thumb) be brought to a particular spatial location (three degrees of freedom), in a particular orientation (one degree of freedom) with a minimum distance between them (one degree of freedom). In addition, different demands placed on the accuracy of, for example, digit pad placement appear to be dealt with by controlling three other parameters: movement speed (or movement time), transport deceleration time and grasp enclose time—these variables are sensitive to changes in accuracy constraints (Wallace and Weeks, 1988; Marteniuk et al., 1990; Jakobsen and Goodale, 1991; Hoff and Arbib, 1993; Bootsma et al., 1994). Task-level degrees of freedom could thus be considered identical to the free parameters of an effector-independent level in a generalized motor programme. Thus, a single reach-to-grasp motor programme would appear to require the specification and possibly control of eight parameters. The bilateral reach-to-grasp task potentially doubles this number.

Our previous results led us to hypothesize that while Parkinson’s disease patients do not appear to be differentially impaired by increases in the number of joint/muscle-level degrees of freedom actively involved in prehensile task performance, they may be impaired by an increase in the number of task-level degrees of freedom. If the numerous task-level degrees of freedom of the bilateral reach-to-grasp task were to present a problem to a Parkinson’s disease patient, a way of dealing with it could be to impose a symmetry constraint on performance (cf. Kelso et al., 1979), to constrain the two hands to move in a similar (homologous) fashion. If the two hands do the same thing at the same instant (move symmetrically) then the number of degrees of freedom that need to be independently specified or controlled is reduced. In this paper, homologous simultaneous movements in the two limbs will be referred to as a symmetrical movement pattern. Different movements in the two limbs will be referred to as an asymmetrical pattern. One plausible prediction of the hypothesis that multiple task-level degrees of freedom present Parkinson’s disease patients with particular problems is that patients would tend to reduce the number of control degrees of freedom in the bilateral
reach-to-grasp task by imposing a symmetry constraint on the two limbs.

Before detailing the manner in which we tested our hypothesis, it is necessary to discuss the results of a similar, recently published, experiment with Parkinson’s disease patients (Castiello and Bennett, 1997). In this study, a group of Parkinson’s disease patients and a group of control subjects were asked to simultaneously reach and grasp a large cylinder (diameter 8 cm) with one hand and a small-diameter (0.8 cm) handle attached to the side of the cylinder with the other hand. It was found that both Parkinson’s disease patients and control subjects appropriately adapted their reaching and grasping movements to the different sizes of the two target objects—an asymmetrical movement pattern. The usual pattern of movement adaptation to different accuracy requirements was observed (Marteniuk et al., 1990; Jakobsen and Goodale, 1991; Bootsma et al., 1994): for the smaller object the deceleration phase of the transport movement was extended and the peak aperture occurred earlier in the movement. At first glance, this result would seem to refute our hypothesis. However, we had previously reported that Parkinson’s disease patients demonstrate a symmetrical pattern in a similar task (Alberts et al., 1996). The difference in the two findings is relatively straightforward to explain. Castiello and Bennett (1997) used a set-up for which a symmetrical movement pattern was not a viable strategy for reducing task-level degrees of freedom. The objects were very different in the width of grasp they required (8 cm and 0.8 cm), type of grasp (whole hand and finger-thumb precision grips), and, distinct from the study of Castiello et al. (1993a, b), ‘the small target (handle) . . . was 16.7 cm lateral to the centre of the large target’ (Castiello and Bennett, 1997, p. 601). The control demands of a bilateral reaching-to-grasp task with this object configuration cannot be effectively reduced by imposing a symmetry constraint; the two grasps have to be adapted to the very different sizes of the two targets and a degree of independent control is still necessary.

In order to test this hypothesis sufficiently, it is necessary to use a task known to elicit simultaneous reaches-to-grasp spontaneously and for which a symmetrical movement pattern is a possible strategy for reducing task-level degrees of freedom. For this reason, two target objects of identical width were used (which therefore demanded the same grasp size) and required subjects to grasp them in the same fashion (index finger and thumb precision grip). The set-up was also carefully arranged such that the objects were the same distance from the starting point for each hand with one object above the other, an arrangement that had been found previously to elicit simultaneous reaches-to-grasp spontaneously (Castiello et al., 1993b). The objects could differ only in the accuracy of digit pad placement required for grasping them. We tested the hypothesis by comparing performance of Parkinson’s disease patients and control subjects in two basic conditions: (i) when they were reaching simultaneously to the small target with one hand and to the large target with the other; (ii) when they were reaching unimanually to the small or large targets or simultaneously to two similar targets (both large or both small). We expected that in the second condition both Parkinson’s disease patients and control subjects would perform with movement patterns appropriate for the accuracy demanded for grasping, consistent with what has been reported elsewhere (Castiello et al., 1993a; Saling et al., 1996; Castiello and Bennett, 1997; Tresilian et al., 1997). In the first condition our hypothesis predicts that the Parkinson’s disease group should show a much more symmetrical movement pattern, with the limbs making homologous movements.

In all subject groups tested, the movement variables sensitive to accuracy constraints are temporal ones: most importantly, transport deceleration time and grasp enclosure time. Thus, since the movement times of the two reaches are expected to be nearly identical, the timing of maximum transport speed and maximum aperture are of particular importance as dependent measures for assessing temporal symmetry. A bilateral reach-to-grasp in which maximum speed and maximum aperture occur at the same time in both limbs is symmetrical in these two variables; the difference in the time of occurrence of maximum speed in the two limbs and of maximum aperture quantifies performance symmetry.

A finding that Parkinson’s disease patients produce symmetrical movements whereas control subjects do not is significant for two reasons. First, it suggests that problems do not arise when performing tasks with several components (such as unimanual reaching-to-grasp) when these components are co-ordinated by an established control programme (Arbib, 1981; Hoff and Arbib, 1993); established motor programmes, whether for controlling joint/muscle-level degrees of freedom or concurrently executed component actions, are left intact in Parkinson’s disease. Secondly, problems arise when there is a need to control and/or adapt two or more motor programmes simultaneously and independently. Experiments in which deficits have been reported in bilateral tasks have invariably required the independent control of two distinct actions which have not previously been performed together (Schwab et al., 1954; Talland and Schwab, 1964; Benecke et al., 1986). Thus, the finding that Parkinson’s disease patients reduce the number of task-level degrees of freedom helps us to understand why the performance of simultaneous movements is disrupted in some tasks but not in others (e.g. Stelmach, 1991; Stelmach and Castiello, 1992).

The set-up used in the experiment is illustrated in Fig. 1. The two target objects were positioned one above the other and were connected by means of an electromagnet. Subjects were asked to pull the upper object free of the lower one with one hand while holding the latter steady with the other hand. The hypothesis discussed above pertains only to the pre-contact phase of this action. It is also of interest to examine how the remainder of the action is performed, culminating in the upper object being pulled free of the lower one. Post-contact performance is of interest for two reasons.
First, there is the requirement to shift from a position-control task (positioning the hand and digits so as to grasp the objects) to a force-control task (grip and stabilize the lower object so that the upper object can be gripped and pulled free). It has often been reported that Parkinson’s disease patients experience difficulties switching from one movement task to another (Weiss et al., 1996, 1997). Secondly, force control in Parkinson’s disease is known to be disrupted (Abbs et al., 1987; Sheridan et al., 1987; Stelmach et al., 1989). The report of the experiment is, therefore, divided into two parts: Part 1 (the pre-contact phase) and Part 2 (the post-contact phase).

General methods

Subjects
Data were collected from seven right-handed Parkinson’s disease patients and seven right-handed age-matched control subjects. However, one control subject and one Parkinson’s disease patient were not included in the analysis of the pre-contact phase because of missing kinematic data. All Parkinson’s disease patients were screened by a neurologist and tested at the same relative time between initial medication and subsequent medication times. Informed consent was obtained from each subject and the study was approved by the Ethics committees of the Arizona State University, USA. Details regarding medication, severity of Parkinson’s disease, gender and age of subjects can be found in Table 1.

Apparatus
Movement of the limbs was recorded using an OPTOTRAK three-dimensional movement monitoring system with three independent cameras. Infra-red emitting diodes (IREDs) were placed on the distal segments of the thumb and index finger of both hands and on the radial styloid process of both wrists. With the cameras placed ~3 m from the experimental work space, the OPTOTRAK system was calibrated prior to each testing session using the manufacturer’s cubic calibration frame so as to be able to record (within the work space) the three-dimensional Cartesian coordinates of the IREDs (in millimetres) relative to an origin and axes defined by the frame. The r.m.s (root mean square) calibration error was always less than the manufacturer’s recommended maximum of 0.4. This gave the system a static positional resolution of <0.2 mm and a dynamic positional resolution of within ~0.4 mm at speeds characteristic of human upper limb movement. IRED position was sampled at 100 Hz.

Grip force and load forces were recorded using a commercial six-dimensional force-torque transducer (Assurance Technologies Inc., Gamma model force-torque transducer and control unit). The transducer is a rigid metal cylinder (diameter 7.5 cm, width 4 cm) which senses force along three orthogonal axes (with their origin in the centre of the device) and the torques about these axes. Only the three force components of the output were recorded; the force along the axis normal to the flat surfaces of the transducer was defined to be grip force (sensor resolution = 0.05 N). The transducer was oriented such that one of the remaining sensor axes was aligned vertically (sensor resolution 0.05 N) and the other horizontally (resolution 0.1 N). A custom-built support ensured that the transducer remained in this orientation. Force data were acquired at a sampling rate of 1000 Hz using the analogue data acquisition unit of the OPTOTRAK system, such that IRED and force data collection were synchronized.

The reaching target consisted of two component objects, one directly above the other, as illustrated in Fig. 1. The force–torque transducer was integral to the bottom object. One end of an aluminum rod was threaded into the top of the force–torque transducer, the other end was threaded into the base of a small cylindrical electromagnet (diameter 2 cm, length 3 cm). The electromagnet could be slid snugly into a hole specially drilled into one of two custom machined Plexiglas cylinders of the same diameter (7.5 cm, equal to that of the force transducer). They had the same gasping width (4 cm) but different grasp surface areas: a small (S) grasp surface area of 0.78 cm², and a large (L) surface area of 8 cm². Surfaces that could be attached to the force transducer to give the lower object the same width as the other two objects and the same grasp surface area as either one of them were constructed. Identical steel discs were glued into the holes drilled in the Plexiglas objects such that when a current was passed through the electromagnet it exerted a force (~12.8 N) on the object. The two Plexiglas objects were of approximately the same weight (small surface object weight = 200 g; large surface object weight = 219 g). The distance between the centres of the top and bottom objects was 15 cm.
Table 1 Description of control subjects and Parkinson's disease patients

<table>
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<tr>
<th>Control subjects</th>
<th>Parkinson’s disease patients</th>
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<td>Subject number</td>
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<td>Sex (years)</td>
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Average (± SD) 63.8 ± 4.4 63.4 ± 6.8

Control 5 and Patient 5 were not included in the pre-contact phase of the analysis because of missing kinematic data.

**Design**

In order to test whether Parkinson’s disease patients have particular difficulty with multiple task-level degrees of freedom, and perform the bilateral reaching task with symmetrical movements so as to reduce their number, it is not sufficient merely to demonstrate that Parkinson’s disease patients are more symmetrical than control subjects. It is necessary to demonstrate this, but is it not sufficient. We also need to demonstrate that in conditions where there are fewer task-level degrees of freedom, Parkinson’s disease patients can adapt their movement patterns to different accuracy demands and that these adaptations are consistent and similar to those of control subjects. In other words, we need to demonstrate that the asymmetry in the bilateral movement pattern of Parkinson’s disease patients that we would predict from their performance in conditions with fewer task-level degrees of freedom is either completely absent or significantly reduced in bilateral performance. For this reason, we included two control conditions. First, following performance of the bilateral reaching task, we required subjects to perform the same action (grasp the two objects and pull the top one from the bottom one) but with sequential rather than simultaneous movements of the two limbs (first reach to the bottom object and after grasping it, reach for the top object with the other hand). Secondly, we included trials (in both the simultaneous and sequential conditions) in which subjects were required to reach for objects with identical accuracy requirements: the top and bottom objects were the same size, either both had large grasp surface (LL) areas or both had small surface areas (SS).

Other control conditions were necessary to determine whether any effects that might be obtained were due to the particular hand used to grasp the object, the type of action subsequently to be performed with the object (grasping and stabilizing versus grasping and pulling), or the position of the object (top or bottom). For this reason, in both the simultaneous and sequential conditions, we included the following sub-conditions: (i) reach to the bottom object with the left hand and the top with the right (LR); (ii) reach to the bottom object with the right hand and to the top with the left (LR); (iii) top object small, bottom object large (SL); (iv) top object large, bottom object small (LS).

These two sets of control conditions resulted in a total of four object conditions (SL, LS, LL, SS) in each of two hand conditions (RL, LR) in two reach conditions (simultaneous, sequential). This gave sixteen conditions overall for each subject in the two groups. Ten trials were performed in each condition. These trials were divided into two blocks of five; these blocks were performed in a pseudorandom order. The simultaneous-reach condition blocks were performed first, followed (after a short break of ~5 min) by the sequential-reach condition blocks.

**Procedure**

The goal of the task was to remove the upper object from the electromagnet. In order to perform this task successfully, subjects had to stabilize the force transducer to remove the upper object, due to the force exerted by the electromagnet. Subjects were given a verbal ‘GO’ signal by the experimenter; upon hearing this command subjects began reaching. They were instructed to perform the movement at a speed at which they normally reach and grasp objects. In addition to no constraint in movement time, fast reaction to the ‘GO’ signal was not required. Subjects were required to remove the upper object while stabilizing the lower object; a precision grip was used for each hand. The upper object was replaced in the same initial position by the experimenter after each trial. In the sequential conditions, subjects were instructed to reach to perform two consecutive unimanual reaches; subjects first reached to the lower object with one hand and then to the upper object with the other hand. In the simultaneous conditions, subjects were not explicitly instructed to initiate or terminate limb movements simultaneously.

**Data reduction and analysis**

Data were processed with custom software written in the LabVIEW application (version 3.1, National Instruments, USA). IRED data were digitally filtered by a dual pass.
through a second-order Butterworth filter with a 12-Hz cut-off (equivalent to a fourth order filter with no phase lag and a cut-off of 9.63 Hz). Force data were similarly filtered (fourth order, no phase lag, cut-off = 10.43 Hz).

The transport component for each hand was based on the position of the marker on the wrist. The transport was analysed by calculating the tangential speed (square root of the sum of squares of the numerical derivatives of the x, y and z coordinates of the transport marker). The grasp aperture was defined as the distance between the thumb and index finger markers. Grip force profiles were analysed for smoothness by calculating normalized jerk values. Jerk was calculated as the third derivative of the grip force profile.

Calculating the onset of transport and aperture was performed by an automatic movement parsing algorithm (Teasdale et al., 1993; algorithm B). The offset of movement was computed from aperture using the same algorithm which was working in reverse. The onsets and offsets were verified by visual inspection by the experimenter; any error was corrected. The following measures were used for both limbs: movement time, maximum aperture, time to maximum aperture, maximum tangential speed, and time to maximum tangential speed. In addition, relative temporal measures were also used and are expressed as a percentage of movement time. In the unimanual conditions relative time values were calculated for each hand. In the bilateral conditions relative time values were calculated by dividing the time to either maximum aperture or maximum speed by total movement time. Total movement time was defined as the time difference between the onset of the first transport component and the end of the last grasp.

Symmetry between limbs was assessed by calculating the difference between the kinematic parameters for each limb on a trial-by-trial basis for unimanual and bilateral conditions. For example, in an asymmetric condition the kinematic variables for the hand reaching to the small surface area were subtracted from the hand reaching to the large surface area. Large differences between limbs suggest that each limb is adapting movement parameters in response to the accuracy requirements of the object to be grasped.

In order to test the symmetry hypothesis it was first necessary to determine if both groups adapted movements in response to object accuracy requirements for unimanual reaches. To determine if the object accuracy requirement influenced movement parameters a group-by-size MANOVA was performed for the unimanual trials. Thus, this analysis would identify whether both groups were showing a similar pattern of results for reaches to the two different surface areas. The absolute time and amplitude measures were used for these analyses. Thus, the purpose of the unimanual conditions was to serve as a control situation to determine if both groups adapted movements in response to the large and small surface areas.

In order to compare performance on unimanual and bilateral trials between groups, symmetry scores were used. The conditions of primary interest were ones in which each hand was reaching to different sized objects. Mean symmetry scores were calculated for each group and were examined via mixed design; a within-group and between-group 2×2 MANOVA. Thus, the purpose of this analysis was two-fold: first, identify any Group×Trial type interactions which would suggest one group is differentially affected by trial type and, secondly, to identify any variables in which there was a simple main effect (trial type) for either group.

**Part 1 (pre-contact phase): Results**

As described in the design section of the methods, in order to test our hypothesis it is necessary to determine (i) whether Parkinson’s disease patients and control subjects displayed distinct temporal movement patterns when reaching for objects of different accuracy requirements in the unimanual control conditions and bilaterally to two similar target objects; and (ii) whether control subjects retained different temporal movement patterns (asymmetrical pattern) when reaching bilaterally for two objects with different accuracy requirements, while Parkinson’s disease patients produced a symmetrical pattern. However, it was first necessary to determine any hand effects or object position effects.

Hand effects were analysed by comparing temporal measures for the left and right hands while subjects reached towards objects with the same accuracy requirements and in the same position (upper or lower object). Results from this analysis revealed that the temporal parameters for the left and right hand were not significantly different from one another, for either group, during reaches to objects that had the same accuracy constraints and which were located in the same position. For the control group, movement time was 750 and 738 ms for the left and right limb, respectively, when both hands reached simultaneously to large target objects. For the Parkinson’s disease group, the movement time was 962 and 978 ms for the left and right limb, respectively, when both hands reached simultaneously to large target objects. Effect sizes were calculated to assess the magnitude of these differences; absolute effect size = |mean (small) − mean (large)|/SD (small). Both groups had an effect size of 0.09. Because these values were well below what Cohen (1988) identified as a large effect size (0.80) we concluded that there was no difference between the movement patterns of the left and right hands and collapsed the data across hand.

In order to rule out any effects produced as a function of object position (pulling versus stabilizing) we compared the parameters for the left and right hand when subjects reached to the same sized target objects simultaneously. Results from these analyses indicated no significant difference between the hand reaching to the upper or lower object for any of the temporal measures. There was a trend, though not significant, for the hand reaching to the lower object to have a shorter movement duration by ~15 and 35 ms for the control and Parkinson’s disease groups, respectively. The effect sizes of these differences were 0.11 and 0.12 for the control and...
Parkinson’s disease groups, respectively, thus we concluded object position was essentially meaningless in terms of affecting movement patterns and collapsed the data across object position.

Did both groups adapt their movements to different accuracy requirements in control conditions?

No significant Group × Size interaction for movement time was present in sequential conditions in which subjects reached to a target object of one size and then with the other hand reached to a different size target. Both groups did, however, show significant simple main effects in that the movement time for reaches to the large target object was significantly shorter than that for reaches to the small target object \[F(1,10) = 12.57, P < 0.01\] for the control subjects and \[F(1,10) = 6.15, P < 0.05\] for the Parkinson’s disease group. Thus, both groups were adjusting their movements to the accuracy requirements of the objects under sequential reaching conditions. Table 2 contains the mean movement times and effect sizes for sequential reaches to different sized targets.

Typical average tangential speed profiles for the transport component for one control subject and one Parkinson’s disease patient are shown in Fig. 2A and C and a group average speed profile is shown in Fig. 2B and D. Examination of these plots reveals that both groups produce speed profiles which are specific to target size. When reaching to the small target maximum speed was reached early, so the deceleration phase was extended. Maximum speed was reached later in reaches to the large target and so the deceleration phase was shorter than in reaches to the smaller target object.

When time to maximum speed was expressed as a percentage of movement time, to control for differences in movement speeds, there was not a significant Group × Size effect. However, both groups did have significant simple main effects. Maximum speed occurred relatively early during reaches to the small target as opposed to reaches to the large target for both groups \[F(1,10) = 23.9, P < 0.001\] for control subjects and \[F(1,10) = 21.07, P < 0.001\] for Parkinson’s disease patients. Quantitatively, control group reaches to the small target resulted in an earlier relative time to maximum speed, at 41% of movement time, while in reaches to the large target, the maximum speed occurred at ~49% of movement time. A similar pattern of results was observed for the Parkinson’s disease group: 42% and 51% for reaches to the small and large targets, respectively.

Average aperture profiles for unimanual sequential reaches to different sized target objects for a control subject and a Parkinson’s disease patient are shown in Fig. 2E and G. Average aperture profiles for the control and Parkinson’s disease groups are illustrated in Fig. 2F and H. On average, both groups produced aperture profiles which were specific to object accuracy constraints. The maximum aperture occurred later during reaches to the large target object than during reaches to the small object.

When expressed as a percentage of movement time, time to maximum aperture occurred relatively early, for both groups, during reaches to the small target. Relative time to

| Table 2 Unimanual reaches to small and large objects: movement times, transport and aperture measures, and effects of object size |
|-------------------------------------------------------|-----------------|-----------------|
| Object size                                         | Small           | Large           |
| Control subjects                                    |                 |                 |
| Movement time (ms)                                  | 841 ± 170       | 702 ± 131       | 0.82 |
| Transport component                                 |                 |                 |
| Maximum speed (mm/s)                                | 785 ± 110       | 805 ± 89        | 0.18 |
| Deceleration time (ms)                              | 499 ± 115       | 362 ± 108       | 1.19 |
| Time to maximum speed (%)                           | 41 ± 3          | 49 ± 5          | 2.67 |
| Aperture component                                  |                 |                 |
| Time to maximum aperture (%)                        | 59 ± 2          | 71 ± 4          | 6.00 |
| Maximum aperture (mm)                               | 96 ± 3          | 97 ± 3          | 0.33 |
| Parkinson’s disease patients                         |                 |                 |
| Movement time (ms)                                  | 982 ± 120       | 911 ± 130       | 0.6  |
| Transport component                                 |                 |                 |
| Maximum speed (mm/s)                                | 675 ± 143       | 770 ± 53        | 0.66 |
| Deceleration time (ms)                              | 569 ± 100       | 463 ± 92        | 1.06 |
| Time to maximum speed (%)                           | 42 ± 3          | 51 ± 4          | 3    |
| Aperture component                                  |                 |                 |
| Time to maximum aperture (%)                        | 65 ± 4          | 76 ± 3          | 2.75 |
| Maximum aperture (mm)                               | 90 ± 3          | 91 ± 3          | 0.33 |

Mean (± SD) and absolute effect sizes for transport and aperture-dependent measures. Absolute effect size = \[\frac{|\text{mean (small)} - \text{mean (large)}|}{\text{SD (small)}}\].
maximum aperture for the control group was 59% for the small target and 71% for the large target [$F(1,10) = 47.91$, $P < 0.001$]. The Parkinson’s disease group displayed the same pattern of results; relative time to maximum aperture was 65% and 76% of movement time for the small and large surface areas, respectively [$F(1,10) = 26.37$, $P < 0.001$]. There was not a significant group-by-size effect for time to maximum aperture when expressed as a percentage of movement time or for maximum aperture.

To further test that both groups scaled movements to target-accuracy requirements under conditions which had fewer task-level degrees of freedom, comparisons were made between bilateral reaches to the same size target objects and unimanual reaches to that same target size (e.g. bilateral reaches to two small targets were compared with unimanual reaches to a small target). Results from this comparison indicated that there were no significant differences, for any of the temporal or amplitude measures for either group, between unimanual and bilateral reaches. For the control group relative time to peak aperture for unimanual reaches was 71% during reaches to the large target and 59% during reaches to the small target, while relative time to maximum aperture was 70% and 60% for bilateral reaches to two large targets and bilateral reaches to two small targets, respectively. A similar pattern of results was observed for the Parkinson’s disease group; unimanual reaches to the large and small targets resulted in relative time to peak aperture occurring at 76% and 65% of movement time, respectively, while bilateral reaches to two large and to two small targets had a relative time to peak aperture of 75% and 65% of movement time, respectively.

**Did the Parkinson’s disease but not the control group show a symmetrical pattern in the bilateral task?**

Movement symmetry was first evaluated qualitatively by plotting individual speed profiles for each limb against one another in the four types of conditions. Plotting the movement of one hand against the other is a convenient graphical means of displaying symmetry between limbs. If the movements of each limb are the same then the plot will be a straight line. Deviations from straightness indicate deviations from symmetry. Examples of average plots of this kind for a Parkinson’s disease patient and control subject are illustrated.
Bilateral prehension in Parkinson’s disease

Fig. 3 Qualitative description of symmetry between limbs for each of the four conditions achieved by plotting the average tangential speed profiles of each limb against one another. The straighter the line the more similar the movements of the limbs. The upper panels represent a typical control subject (dotted line) and the control group on average (solid line). The lower panels describe a typical Parkinson’s disease patient (dotted lines) and the Parkinson’s disease group on average (solid line). Plots A and E represent unimanual reaches to large objects; plots B and F represent bilateral reaches to two large objects. Plots C and G represent unimanual reaches to two different size objects; plots D and H represent bilateral reaches to two different size objects.

in the different panels of Fig. 3, along with average plots for each group. Figure 3 (A, B, E and F) demonstrates that both groups make symmetrical movements for unimanual and bilateral reaches to two targets with the same accuracy constraints. Examination of Fig. 3C and G reveals that individual limb movements are highly asymmetrical, for both the control subjects and Parkinson’s disease patients, when they perform sequential unimanual reaches to different sized target objects. Symmetry between limbs for bilateral simultaneous reaches to different sized target objects, for control subjects and Parkinson’s disease patients, is illustrated in Fig. 3 (D and H, respectively). For Parkinson’s disease patients, speed profiles for each limb are nearly identical as reflected by a line which is approximately straight (Fig. 3H).

In the bilateral simultaneous conditions in which each hand reached to a different sized target object the control group had a mean total movement time of 854 ms compared with 1081 ms for the Parkinson’s disease group \([F(1,10) = 22.91, P < 0.001]\).

Average tangential speed profiles for the transport component for subjects from both groups and an average profile for both groups for bilateral reaches to different sized objects are illustrated in Fig. 4. Inspection of Fig. 4A and B reveals that the typical control subject and the control group as a whole produced speed profiles specific to object accuracy constraints such that maximum speed occurred earlier for the hand reaching to the small object compared with the hand reaching to the large object. Speed profiles for the typical Parkinson’s disease patient and the Parkinson’s disease group in general were similar for each limb during simultaneous reaches to different sized objects (Fig. 4C and D).

Inspection of average aperture profiles for both groups, in the bottom panels of Fig. 4, reveals a similar pattern of results to the transport component for each group. The control subject, and the control group in general (Fig. 4E and F), produced two unique aperture profiles which were scaled with respect to target accuracy, such that peak aperture occurred earlier for the hand reaching to the small object. In contrast, the Parkinson’s disease patient, and the Parkinson’s disease group in general (Fig. 4G and H), produced aperture profiles which were similar for both hands, even though each hand was reaching to a different size object.

In bilateral reaches to different sized objects, the
Parkinson’s disease group produced movement patterns which were significantly more symmetrical than the control group. Difference scores were used to assess symmetry between limbs. For the transport component, relative time to maximum speed difference was significantly greater for the control group (6%) compared with the difference score for the Parkinson’s disease group (3%) \[F(1,10) = 14.89, P < 0.01\], with an effect size of 1.5. The Parkinson’s disease group also produced more symmetrical aperture profiles than the control group. Relative time to maximum aperture difference for the left and right hands was 10% for the control group and 1.7% for the Parkinson’s disease group \[F(1,10) = 76.83, P < 0.001\], with an effect size of 4.15.

Difference scores were also used to assess how the effects of trial type (sequential or simultaneous reaches) interacted with the two groups when they were reaching to objects with different accuracy constraints. Table 3 contains difference scores for the transport and aperture components, interactions, and effect sizes. Analyses of these difference scores indicated that neither group displayed a trial-type effect for differences in maximum speed. A trial-type effect was present for the Parkinson’s disease group for the relative time to maximum speed difference. In the unimanual conditions relative time to maximum speed difference was 10.2% while in the bilateral conditions it decreased to 3% \[F(1,10) = 5.65, P < 0.05\]. The difference between time to maximum speed, both absolute and relative, was not significantly affected by trial type for the control group.

A trial-type effect for time to maximum aperture difference for the Parkinson’s disease group was present. For the unimanual conditions the difference was 159 ms while it decreased to 16 ms for the bilateral conditions \[F(1,10) = 30.36, P < 0.001\]. There was no trial-type effect for the control group. There was a group-by-trial type interaction for time to maximum aperture difference \[F(1,10) = 17.84, P < 0.01\], illustrated in Fig. 5. Time to maximum aperture difference for the Parkinson’s disease group became significantly smaller when they performed reaches in the bilateral conditions as opposed to the pattern for the control group, in which time to maximum aperture difference was similar for unimanual and bilateral reaches.

The relative time to maximum aperture difference produced a similar pattern of results. For the Parkinson’s disease group there was a trial-type effect for relative time to maximum aperture difference; in the unimanual conditions the difference (comparing reaches to different size objects) was 10.6% of.
Bilateral prehension in Parkinson’s disease

Table 3 Reaching to large versus small surface areas (differences) and the effects of Parkinson’s disease on these differences

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unimanual reaching</th>
<th>Bilateral reaching</th>
<th>Trial type</th>
<th>Group × Trial type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control subjects</td>
<td>PD patients</td>
<td>Control subjects</td>
<td>PD patients</td>
</tr>
<tr>
<td>Maximum speed difference (mm/s)</td>
<td>107 ± 41</td>
<td>103 ± 38</td>
<td>0.10</td>
<td>67 ± 18</td>
</tr>
<tr>
<td>Time to maximum speed difference (%)</td>
<td>9.7 ± 2</td>
<td>10 ± 4</td>
<td>0.15</td>
<td>6 ± 2</td>
</tr>
</tbody>
</table>

Aperture component

<table>
<thead>
<tr>
<th></th>
<th>Unimanual reaching</th>
<th>Bilateral reaching</th>
<th>Trial type</th>
<th>Group × Trial type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control subjects</td>
<td>PD patients</td>
<td>Control subjects</td>
<td>PD patients</td>
</tr>
<tr>
<td>Maximum aperture difference (mm)</td>
<td>5 ± 2</td>
<td>6 ± 2</td>
<td>0.50</td>
<td>5 ± 2</td>
</tr>
<tr>
<td>Time to maximum aperture difference (ms)</td>
<td>80 ± 24</td>
<td>159 ± 36</td>
<td>3.29</td>
<td>86 ± 22</td>
</tr>
<tr>
<td>Time to maximum aperture difference (%)</td>
<td>11 ± 4</td>
<td>10 ± 4</td>
<td>0.25</td>
<td>10 ± 2</td>
</tr>
</tbody>
</table>

PD = Parkinson’s disease; n.s. = not significant. Mean (± SD) difference scores (subtracting values of limb reaching to the large surface area from the values with the limb reaching to the small surface area) and for transport and aperture-dependent measures are shown; absolute effect size = |mean (control) – mean (patient)|/|SD (control)|. Effects of trial type for each group are shown and Group×Trial type interactions are also listed. *P < 0.05.

Fig. 5 Individual (thin black lines) and group (thick grey lines) mean values for the difference in the time to maximum aperture for unimanual and bilateral reaches to two different size objects. Difference values were computed by subtracting the time to maximum aperture for the limb reaching to the small object from the time to maximum aperture for the limb reaching to the large object.

total movement time compared with a 1.7% difference during the performance of bilateral reaches \(F(1,10) = 40.37, P < 0.001\). The control group did not demonstrate a significant difference as a function of trial type. There was a significant Group×Trial type interaction for relative time to maximum aperture difference, which is illustrated in Fig. 6 \(F(1,10) = 12.83, P < 0.01\). As Fig. 6 illustrates, all Parkinson’s disease patients had smaller difference scores in the bilateral conditions than in the unimanual conditions. The control group maintained similar levels of asymmetry between aperture components in both types of reaches, with difference scores of 11.8% and 10% for unimanual and bilateral reaches, respectively.

Bilateral transport initiation

Results indicated that the Parkinson’s disease group had a significantly longer interval between the initiation of the two transport components than the control group \(F(1,10) = 22.23, P < 0.001\). The initiation difference between
transports for the control group averaged 30 ms while the difference for the Parkinson’s disease patients was more than twice that at 65 ms.

**Bilateral movement termination**

In the bilateral trials, the time interval between the offset of each aperture component was calculated for offset analysis. The offset difference between hands was significantly greater for the Parkinson’s disease group (106 ms) as compared with 50 ms for the control group $[F(1,10) = 16.20, P < 0.01]$. When the offset difference was expressed as a percentage of the total movement time, a similar pattern of results was shown. For the Parkinson’s disease group the offset difference accounted for 9% of their total movement time, while it was only 5% for the control group $[F(1,10) = 22.30, P < 0.001]$.  

**Part 1: Discussion**

The purpose of this study was to examine the movement patterns of Parkinson’s disease patients while they were performing a natural task which requires the co-ordination of multiple task-level degrees of freedom. It was hypothesized that when Parkinson’s disease patients, unlike their age-matched counterparts, perform a bilateral reach to two target objects with different accuracy constraints they would produce symmetrical movement patterns between the limbs. Results confirmed this hypothesis.

The results indicate that Parkinson’s disease patients and control subjects are able to adjust movement parameters of the transport and grasp components appropriately, in response to accuracy requirements of the target object, both when they performed two consecutive unimanual reaches and when they reached to two similar objects simultaneously. Evidence for these adjustments of movement parameters came in the form of a longer movement time during reaches to the small surface area compared with reaches to a large surface area. Further evidence for scaling came when the time to maximum aperture and time to maximum speed were expressed as percentages of movement time; again consistent with previous studies (Wing et al., 1986; Bootsma et al., 1994), reaches to the small surface area resulted in shorter relative times to both maximum speed and aperture.

When reaching simultaneously to objects of different sizes, control subjects scaled movement patterns similarly to the scaling observed in unimanual sequential reaches and in bilateral reaches to two objects with the same accuracy constraints. Difference or symmetry scores for the unimanual and bilateral conditions were used to examine the similarity of the movements of the two limbs. Analysis of these scores and kinematic profiles revealed that the Parkinson’s disease group showed more similarity between limbs under bilateral reaches to different sized targets than they did when performing sequential reaches to different sized objects. The control group maintained similar levels of symmetry between limbs for both unimanual and bilateral reaches.

A similar pattern of results was displayed for the grasp component. In the bilateral conditions, the two aperture components were highly symmetrical for the Parkinson’s disease group, while the control group maintained a similar level of asymmetry or independence between the two aperture components. Figure 6 illustrates that, in the unimanual sequential conditions, both groups had marked differences between reaches to objects with a small surface area versus a large surface area. The control group was able to maintain this difference for bilateral simultaneous reaches; this can be
interpreted as adapting the movement of each limb to the specific accuracy requirements of the two objects being grasped. However, the movement patterns produced by the Parkinson’s disease group became more similar even though they were reaching to different sized target objects. Thus, when performing bilateral reaches, they did not adapt two different grasp components for each limb in response to the accuracy requirements of the objects. Inability to maintain scaling under bilateral reaches suggests that Parkinson’s disease patients have a different method of planning and controlling movements that require the co-ordination of multiple task-level degrees of freedom.

The finding that Parkinson’s disease patients produced symmetrical movement patterns in simultaneous reaches to two different objects confirms our hypothesis that they have problems with simultaneously specifying and/or concurrently controlling multiple task-level degrees of freedom. This helps us to understand why in some tasks involving both limbs simultaneously, Parkinson’s disease patients show no significant additional impairment whereas in others they do. When a bilateral task involves relatively few task-level degrees of freedom (e.g. the same number as the unimanual task being used in the control conditions) we find little evidence of increased impairment in the bilateral task relative to the unimanual control task (Stelmach and Worringham, 1988a; Tresilian et al., 1997). When the number of independent task-level degrees of freedom is increased, increases in impairment are observed (Schwab et al., 1954; Benecke et al., 1986).

If Parkinson’s disease patients do have problems with the independent specification and/or control of multiple task-level degrees of freedom as suggested then it would be expected that strategies or deficits should be observed in all tasks with at least as many such degrees of freedom as the bilateral reach-to-grasp task used here. As mentioned in the Introduction section, if the task is such that the strategy of producing symmetrical movements to reduce the number of independent degrees of freedom is not available to a person, then it cannot be used. We interpret the failure of Castiello and Bennett’s (1997) Parkinson’s disease patients to show symmetrical patterns to be due to the strategy of reducing task-level degrees of freedom being unavailable in their version of the bilateral reach-to-grasp task. It would be expected, however, since the number of degrees of freedom is the same in both versions of the task, that Castiello and Bennett’s Parkinson’s disease patients would show deficits or performance differences not found in the Parkinson’s disease group described here. This was, in fact, the case. Castiello and Bennett (1997) found that their Parkinson’s disease group showed relatively large adjustments to the ‘final transport phase of the left arm under bilateral conditions’ (p. 593) (as indexed by multiple speed peaks in the deceleration phase of the tangential speed profile of the wrist). Such behaviour was not observed in our Parkinson’s disease group. We interpret these differences to mean that, while both Parkinson’s disease groups had particular problems when reaching bilaterally to objects of different accuracy requirements, different task conditions led the two groups to express these problems in different ways.

The known neuroanatomical effects of Parkinson’s disease provide support for the idea that Parkinson’s disease reduces the capability to control and organize two simultaneous reaches. As described by Wichmann and DeLong (1993), decreased levels of dopamine result in a decrease in the output of the striatum in Parkinson’s disease patients, thus decreasing the inhibitory action on the globus pallidus internal segment which projects to the ventral lateral thalamus. Thus, Parkinson’s disease patients probably have more output coming from the globus pallidus internal segment, which in turn allows for more inhibition of the ventral lateral thalamus. Projections from the ventral lateral thalamus function to excite the supplementary motor area (SMA). However, due to the greater output of the globus pallidus internal segment, the ventral lateral thalamus has decreased output to the SMA which results in decreased SMA output (Contreras-Vidal and Stelmach, 1996; Cunnington et al., 1996).

It has been suggested by Wiesendanger (1986) that the SMA is involved in the planning and production of complex movements. A recent study by Uhl et al. (1993) revealed that SMA involvement is greater for bilateral movements in which movements of each hand are asymmetric as opposed to symmetric movements. These and other studies (for review, see Cunnington, et al., 1996) clearly indicate that the SMA operates bilaterally, with complex inter-hemispheric interactions modulating the activity of the left and right primary motor areas. The SMA is therefore ideally suited to play a significant role in the planning and co-ordination of bilateral movements which require asymmetric performance (Cunnington et al., 1996).

In an early study of patients that had reduced SMA output, due to SMA lesions, Laplane et al. (1977) reported these patients had problems co-ordinating both limbs and hands. These researchers suggested that the limbs are not able to ‘share the motor load’ causing patients to exhibit bilateral movements adapted in similar ways, thereby reducing any unique variation between them. It appears this occurs in Parkinson’s disease patients. It appears that control subjects are able to generate and operate two motor programmes that are distinct from one another simultaneously which accounts for their ability to produce movements with unique kinematic patterns which are consistent with their movement patterns when they performed more simple movements (e.g. unimanual reaches). In contrast, Parkinson’s disease patients may be simplifying their mode of controlling bilateral movements by generating one central command which serves to control both limbs, resulting in highly symmetric movements under non-homologous task conditions.

Evidence of difficulty in the initiation of simultaneous movements for Parkinson’s disease patients is the clear asynchrony in the initiation of two transport components. The time difference between initiating the two transports was 30 ms for the control group while for the Parkinson’s disease
group it was more than double at 65 ms. A similar effect was found for the offset difference between hands. The Parkinson’s disease group had an offset difference of 100 ms, while the control group had an offset difference of 51 ms. These differences in initiation and termination of movement provide further evidence that Parkinson’s disease patients experience some difficulty in generating simultaneous movements, as first described by Schwab et al. (1954) and Benecke et al. (1986).

Part 2 (post-contact phase): Introduction
The post-contact phase of the reach-to-grasp task involves the period of transition for the reach-to-grasp (position control) phase to the pull (force control) phase. Previous results would suggest that such a transition would be temporally extended in Parkinson’s disease patients (Rand et al., 1994; Weiss et al., 1997). Thus, we tested whether this was the case by estimating the time period between object contact and the onset of pull-force production, and assessing whether this period was longer in the Parkinson’s disease group than the control group.

Many reports have suggested that force control is disrupted in Parkinson’s disease (Abbs et al., 1987; Sheridan et al., 1987; Stelmach et al., 1989; Kunesch et al., 1995). Stelmach and Worringham (1988b) found that Parkinson’s disease patients took longer to reach peak force, had a lower rate of force development, and produced a more irregular force time pattern than age matched control subjects. Other researchers have reported similarly disrupted force control patterns in Parkinson’s disease patients (Abbs et al., 1987; Sheridan et al., 1987). Some of the tasks used to assess force control in Parkinson’s disease have been the unfamiliar, contrived laboratory tasks and may have involved a significant learning and/or cognitive component which may have confounded results. Prehension provides a normal model task for the study of force control in Parkinson’s disease, but this aspect of prehensile behaviour has received relatively little attention in this context despite having been studied extensively in the healthy population (Johansson and Westling, 1984; Flanagan et al., 1993). We therefore report the force production characteristics of the Parkinson’s disease patients and control subjects in the transition and stabilization phases of the task investigated here. We measured grip force and vertical load force on the bottom object. If Parkinson’s disease adversely affects force control, irregularities in the production of grip and load forces should be expected as well as disruptions in the parallel co-ordination between these forces.

Part 2: Results
The time duration from contact of the force transducer to lifting of the object (force time) was significantly greater for the Parkinson’s disease group. On average it took the Parkinson’s disease group 1198 ms from the time of contact to lift off, while the control group took 545 ms [F(1,12) = 19.80, P < 0.001].

Transition phase
The Parkinson’s disease group spent a significantly longer time in the transition phase than the control subjects [F(1,12) = 18.76, P < 0.001]. Parkinsonian subjects took 375 ms from contact with the force transducer to onset of stabilization of force, while the control subjects spent 125 ms in the transition phase. There were no significant effects as a function of hand or object accuracy requirements of the upper or lower object for any of the temporal or amplitude variables for either group.

Stabilization phase
Time spent in the stabilization phase (time from grip-force onset to lift off) was significantly longer for the Parkinson’s disease group (823 ms compared with 419 ms for the control group) [F(1,12) = 10.66, P < 0.01]. However, the relative time (time spent in the stabilization phase/force time) spent in the stabilization phase did not differ significantly between groups.

There were no group differences in any of the amplitude parameters of grip force, such as maximum grip force, safety margin or relative safety margin (safety margin/maximum grip force). However, the manner in which each group achieved their grip force was different. Typical time normalized grip-force profiles for an individual subject from each group are shown in Fig. 7. Examination of this figure reveals that the control subject reached peak force in a smooth manner, while the Parkinson’s disease patient developed force in a staircase manner.

Normalized jerk scores were used to examine the smoothness of grip force during the stabilization phase. The Parkinson’s disease group had significantly greater jerk values than the control group. The average jerk value for the
Bilateral prehension in Parkinson’s disease

Fig. 8 Typical grip (thick lines) and load/pulling (thin lines) force profiles for the entire movement. Profiles from four control subjects are shown in (A), while (B) contains profiles from four Parkinson’s disease patients (PD).

Parkinson’s disease group was 889 while control subjects had an average of 267 [F(1,12) = 12.62, P < 0.01].

Typical grip and load force profiles for control subjects and Parkinson’s disease patients are illustrated in the top and bottom sections of Fig. 8. Inspection of these graphs illustrates the typical finding that force development during the stabilization phase is different for the two groups. The control subjects produce smooth grip and load force profiles, while grip and load force profiles for the Parkinson’s disease patients are irregular. To assess the co-ordination between the two forces, grip and load force were plotted against one another (Fig. 9). The upper panels in Fig. 9 illustrate that the control subjects’ plots are relatively linear over the majority of the stabilization phase, suggesting a tight co-ordination between the two force components. The Parkinson’s disease patient plots (bottom panels of Fig. 9) are very irregular and far from linear; this irregularity is not systematic over trials suggesting little co-ordination between the two force components.

Part 2: Discussion

The task used in the present study has provided results which clearly indicate that Parkinson’s disease affects force production. These results differentiating Parkinson’s disease patients from their healthy peers include less smooth (greater jerk) grip force profiles and an irregular pattern of grip and load force. Perhaps the most notable difference is seen when grip force is plotted as a function of resultant load force. The control subjects have an almost linear relationship between the two forces while the Parkinson’s disease patients’ plots are very irregular and far from linear.

Sheridan et al. (1987) suggested that increased variability of movements (in time and space) exhibited by Parkinson’s disease patients is related to an inherent variability in force production. Three possible explanations were posited for this increased force variability: (i) an incorrect computation of the required force; (ii) a defective memory for the computed forces; and (iii) a noisy output from the motor system. Stelmach et al. (1989) compared Parkinson’s disease patients’ and young control subjects’ abilities to produce a target level force (percentage of maximum force) on an isometric force production task. Results indicated that Parkinson’s disease patients produced less force, but they were just as accurate in reaching the target level force as young subjects. Based on these results, it was concluded that Parkinson’s disease patients’ ‘internal model’ of producing appropriate force
magnitudes is intact. Evidence for an accurate internal model comes from the results that demonstrate no difference between groups in their maximum grip force, safety margin and relative safety margin. These results coupled with the findings reported by Stelmach et al. (1989) oppose the idea that Parkinson’s disease produces errors in the computation of the necessary force which would in turn lead to more variable movements. Stelmach and Worringham (1988b) and Stelmach et al. (1989) have shown more variability in the force time pulse of Parkinson’s disease patients. This observed variability would lead to the variable movements seen in Parkinson’s disease patients.

An early study by Johansson and Westling (1984) offers a tenable explanation regarding the co-ordination of grip and load force observed in the age-matched control subjects. They posited that force co-ordination between grip and load forces could be defined by a memory trace which receives intermittent updating. They suggest that a reliance on a memory trace conforms to the principles of motor adaption accomplished by anticipatory or predictive control operating on the basis of a flexible neural representation within the brain that includes features of the external world. Thus, the grip and load force commands may be simultaneously executed with relation to the friction between the fingers and the object.

The parallel change in grip force and load force for control subjects suggests that their system is not operating on a closed-loop type of feedback because if that was the case then there would have to be a temporal lag between the grip and load force components. Rather, the data suggest that the healthy system is using a predictive feed-forward mode of control as evidenced by the linear relationship between grip and load force. Present results suggest that Parkinson’s disease affects the operations of this predictive feed-forward model. Based on the irregular and nonsystematic grip and load relationship demonstrated by Parkinson’s disease patients, it is contended that Parkinson’s disease changes the mode of force control from feed-forward to feedback. Results from previous studies, that have shown Parkinson’s disease patients have difficulty using predictive information to improve performance (Bloxham et al., 1984), lend support to the change from a feed-forward to feedback mode of control. It is suggested that the use of this feedback mode of control is due to the inability of Parkinson’s disease patients to predict consistently the amount of load (pulling) force they are exerting or the amount of grip force they need to exert to

Fig. 9 Grip force plotted as a function of load force for four control subjects (A) and four Parkinson’s disease patients (B).
stabilize the object. Inability to build this predictive feedforward model could be due to an improper scaling of motor output (Wierzbicka et al., 1991). This improper scaling of output is a tenable explanation for the irregular grip force patterns of Parkinson’s disease patients.

These results do not allow us to determine whether the absence of the grip-load force co-ordination is due to a problem co-ordinating forces developed by two limbs (one hand is gripping while the other pulls) or due to an uncoordinated downward pushing force developed by the gripping hand or to some combination of the two. It is also possible that the presence of an action tremor could be a major contributor to the observed discoordination force pattern. This is quite plausible if the tremor is present in both limbs and out of phase in the two limbs. Such a tremor would naturally make co-ordinating forces bilaterally quite difficult. Future experiments are planned to dissociate between these possible explanations.

**General conclusions**

The results from the pre-contact phase confirmed the prediction of our hypothesis, that Parkinson’s disease patients have difficulty specifying and regulating multiple task-level degrees of freedom independently. Both Parkinson’s disease and control groups performed the bilateral reach-to-grasp task with movements of the left and right arms which began and ended approximately simultaneously. In addition, in the control conditions, both groups adapted their movements to increased accuracy requirements by extending the transport deceleration time and the grasp enclose time. When reaching for two objects with different accuracy requirements, control subjects retained a temporal movement organization appropriate for the object being reached for; the transport deceleration time and the grasp enclose time were extended for the smaller grasp surface area. Thus, control subjects performed with an asymmetrical movement pattern. Parkinson’s disease patients, in contrast, showed little retention of the normal temporal adaptations to different accuracy requirements; they performed with a very symmetric movement pattern. This implies that Parkinson’s disease patients were not independently adapting or controlling the two reaches-to-grasp in response to differential accuracy requirements, but the control subjects were. We interpret this to mean that the Parkinson’s disease patients were simplifying the control problem by reducing the number of variables that were specified independently. The results from the post-contact phase suggest that Parkinson’s disease disrupts the normal operations of the feedforward mode of control responsible for the parallel increase in grip and load force.

**Acknowledgement**

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**References**


