Stability of reach-to-grasp movement patterns in Parkinson’s disease

James R. Tresilian,1,* George E. Stelmach1 and Charles H. Adler2

1Motor Control Laboratory, Arizona State University, Tempe and 2Mayo Clinic, Scottsdale, USA

Correspondence to: George E. Stelmach, Motor Control Laboratory, Arizona State University, Tempe, AZ 85287–0404, USA

*Present address: Department of Human Movement Studies, University of Queensland, Brisbane, Queensland 4017, Australia

Summary

The performance of patients with Parkinson’s disease on two reach-to-grasp tasks was compared with that of age-matched control subjects. The aim of the study was to determine whether Parkinson’s disease patients have problems coordinating concurrently executed tasks within the same system of effectors in a natural context and whether such problems would be exacerbated by increases in task difficulty. We examined how subjects concurrently executed the transport and grasp components of reach-to-grasp movements in the presence of two types of change in task demands: (i) increases in demands for accurate digit pad placement and (ii) use of two reach-to-grasp tasks, i.e. the standard unimanual task and a bimanual task which increased the control and coordination demands relative to the unimanual task. If Parkinson’s disease patients have coordination problems they should demonstrate increased impairment with increasing accuracy demands and in the bimanual task; any such differences should be absent or much smaller in the control group. The Parkinson’s disease group showed substantial impairments in all conditions, moving about 30% slower than the control group, with much increased jerking and with signs of difficulty controlling the speed of movement. However, there were no consistent indications that the Parkinson’s disease group were differentially impaired on the bimanual task nor that movement deficits increased with increasing accuracy requirements. Grasp and transport components were coordinated similarly by Parkinson’s disease and control groups in both reach-to-grasp tasks, and the Parkinson’s disease group co-ordinated the two limbs in the bimanual task effectively and in a fashion similar to that of the control group. These results are interpreted to mean that higher levels (effector-independent levels) of motor programming are preserved in Parkinson’s disease and that execution of a motor programme need not be compromised by increasing the number of muscle-joint-level degrees of freedom which are used.

Keywords: Parkinson’s disease; motor co-ordination; reach-to-grasp; effector-independent motor programming

Abbreviations: ANOVA = analysis of variance; D = size parallel to the reach axis; H = height of grasp surface; IRED = infrared emitting diode (marker); MT = movement time; PC = principle component; PCA = principle components analysis

Introduction

Prehension behaviours provide both natural and convenient tasks for the study of coordination and the exploration of coordination deficits in neurological disorders affecting movement, such as Parkinson’s disease. The pattern of concurrent execution of two identifiable functional components of prehension behaviours are typically studied: a transport component and a grasp or manipulation component (Jeannerod, 1981, 1984). In the reach-to-grasp prehension task people reach out and pick up a target object by opposing the pads of the fingers (or often just the index finger) and thumb. Movements of the reaching limb up to the moment of object contact are analysed. The movement that takes the hand to a position in which the object can be grasped constitute the transport component of this task; movements of the fingers which shape the hand into a grasp configuration suitable for gripping the object define the grasp component.

© Oxford University Press 1997
The task in which a person reaches with one hand from a static, closed hand posture (fingers partially flexed, thumb and index finger touching) will be called the ‘standard prehension task’. The standard prehension task provides a simple and natural task with which to examine the proposal of Benecke et al. (1986) who suggested that Parkinson’s disease leads to a problem with concurrent execution of functionally independent motor programmes with the same limb (see Müller and Stelmach, 1992; Castiello et al., 1993). Furthermore, the fact that the standard task has a distal grasp component and a proximal transport component makes it a potentially good candidate task for the exploration of the consequences of basal ganglia dysfunction in Parkinson’s disease, since the pallidal output of the basal ganglia in primates has been found to be directed towards the ventrolateral thalamus, which selectively innervates the hand representation in the primary motor cortex (Nambu et al. 1988; Holsapple et al., 1991). This suggests that the grasp component may be differentially impaired relative to the transport component, leading to observable problems of coordination. However, significant grasp–transport coordination impairments have not been observed in Parkinson’s disease patients’ performance of the standard task (Müller and Stelmach, 1992; Castiello et al., 1993; Saling et al., 1996); Parkinson’s disease patients were found to be slower (bradykinesia) and would often reach a smaller peak aperture (hypometria) than age-matched control subjects, but in other respects task performance was similar in the two groups. Castiello et al. (1993) did report one small possible coordination difference between the two groups: on average Parkinson’s disease patients tended to start opening the index finger and thumb aperture some 40–50 ms later than control subjects, relative to the onset of the transport movement. This difference was not functionally significant and is not observed when the hand starts from an open posture rather than a closed one (Saling et al., 1996).

It appears, therefore, that Parkinson’s disease does not necessarily lead to any significant impairment of the central processes involved in organizing the concurrent execution of functionally independent motor programmes which are executed by the same effector system. It is possible that the well-established motor programmes controlling the coordination of subcomponents in the performance of everyday actions such as reaching and grasping are not directly affected by the disease. Performance of such tasks is, of course, degraded, but the observed performance deficits are the same as those observed in other tasks and are possibly the result of the same mechanism in all tasks; difficulties in executing movements with a motor output system which is seriously disrupted by pathological descending signals which lead to tremor and other pathological influences which significantly limit the speed of movement execution (bradykinesia). Other task-independent deficits appear to include impairment of the ability to prepare and initiate voluntary movement properly (e.g. Stelmach et al., 1986; Brown and Marsden, 1991; Latash et al., 1995), and problems with the control of posture and the integration of postural tasks with active movement tasks (e.g. Bazalgette et al., 1987; Latash et al., 1996). Parkinson’s disease may, therefore, leave the basic patterns of coordination between concurrently executed task components relatively unaffected, impairing instead other aspects of movement control.

The following question arises: to what extent do basic patterns of coordination remain unaffected in Parkinson’s disease when a task’s execution is made more demanding? We explored this question using the reach-to-grasp task by studying the effects of two manipulations of execution demands in a group of Parkinson’s disease patients and a group of age-matched control subjects. The first manipulation simply involved variation of the accuracy of digit pad placement required to grasp the target object. A set of six target objects was constructed with different accuracy requirements ranging, in a step-by-step fashion, from relatively undemanding (large grasp surface) to demanding (small grasp surface). It is known that the pattern of concurrent execution of the transport and grasp components adapts in a predictable fashion to increasing accuracy requirements in healthy people (Wallace and Weeks, 1988; Jackobsen and Goodale, 1991; Bootsma et al., 1994). The second manipulation involved requiring the subjects to use different effectors to grasp the target object. Grasps with two different effector systems were required: (i) the standard unimanual task and (ii) a bimanual task requiring index finger pad opposition, which we had previously studied in young healthy subjects (Tresilian and Stelmach, 1997). In this study we established that the pattern of concurrent grasp and transport execution is the same in the bimanual task as in the standard task. This result suggests that there is a level or stage of motor programming in reaching to grasp in which the pattern of coordination between the two components is represented but the effectors are unspecified (cf. Bernstein, 1967; Raibert, 1977; Saltzman, 1979; Schmidt, 1980; Latash, 1993).

The bimanual task increases the coordination demands not only by requiring coordination of the two limbs but also by increasing the number of degrees of freedom, at both the joint and muscle level, during the reach-to-grasp movement. The standard task involves two joint-level degrees of freedom at the shoulder, one at the elbow (there is little or no movement of the trunk and the hand is placed in an initial orientation appropriate for grasping the object and so no pronation/supination of the wrist is required), and only the degrees of freedom of the index finger appear to be involved in grasp formation; the thumb remains in a more or less constant position relative to the hand (Wing and Fraser, 1983). This gives a total of five joint-level degrees of freedom. In the bimanual action, the two degrees of freedom of each shoulder and one at each elbow (total of six) are minimally involved. Analysis of the behaviour of young participants revealed that wrist and finger degrees of freedom
were also being used (Tresilian and Stelmach, 1997). Thus, at least 10, possibly 12, joint-level degrees of freedom are involved. Increasing the number of degrees of freedom increases the control demands, these demands can be reduced by freezing redundant degrees of freedom, thus obviating the need for controlling them during movement execution (Bernstein, 1967). This strategy is observed in novice performers of complex movement tasks (e.g. Vereijken et al., 1992) and there is some evidence that Parkinson’s disease patients restrict the number of degrees of freedom concurrently controlled during execution of drawing movements (Teulings et al., 1997).

The manipulations of the accuracy requirements and effector system both systematically varied the execution demands of the reach-to-grasp task. If basic patterns of coordination represented by the CNS at an effector-independent level of motor programming are unaffected in Parkinson’s disease, then it would be expected that they would be preserved in performance. Thus, we would expect Parkinson’s disease patients to show similar patterns of concurrent grasp–transport execution in the two prehension tasks and similar patterns of adaptation to changing accuracy constraints. Benecke et al. (1987) previously reported significant increases in movement time by Parkinson’s disease patients when an additional task involving finger movement was executed concurrently by the same limb that executed the primary task (elbow flexion). Such increases were not observed in control subjects. This demonstrated an impairment, but not one that could be interpreted as affecting the control of coordinative patterns, consistent with the proposal that Parkinson’s disease may impair a stage of motor control at a lower level than that at which coordinative patterns are represented. If this hypothesis is correct, then we expect that Parkinson’s disease patients will show an increase in their task-independent deficits (slowness, hypometria, lack of smoothness) with increasing task demands, but a preservation of the patterns of coordination and adaptation. To investigate these possibilities, the pattern of concurrent grasp–transport execution, and adaptation to changing accuracy demands, were examined in the standard and bimanual reach-to-grasp tasks. Detailed movement kinematics were recorded and analysed in a group of Parkinson’s disease patients and an age-matched control group. The data were examined for evidence of execution deficits and coordination problems.

All Parkinson’s disease patients were on their normal medication schedule at the time of testing (see Table 1). There were three male and three female control subjects with a mean age of 66 years (range 62–74 years). Subjects were volunteers who gave informed consent and received financial reimbursement for their participation. The study was approved by the local ethics committee. Note that due to technical problems with the data acquisition equipment, data from >75% of the trials obtained from Patient 5 in the unimanual task were lost; no unimanual trial data from this subject were included in the analysis.

Apparatus
Data were collected using an Optotrak™ opto-electronic 3D movement recording system with three independent cameras. This system recorded the 3D (x, y, z) positions of infrared emitting diode markers (IREDs) placed on the hands and wrist at a sampling rate of 150 Hz. This system had a static positional resolution throughout the experimental workspace of <0.5 mm and a dynamic spatial resolution during speeds characteristic of human arm movements of <0.8 mm. For unimanual trials, IREDs were placed on the wrist (styloid process of the radius), the metacarpophalangeal joint (knuckle) of the index finger, the thumb nail and on the distal segment of the index finger (just distal to the second interphalangeal joint). For bimanual trials, IREDs were placed on the two wrists, on the knuckles of the index fingers and on the distal segments of the index fingers.

Six different target objects were constructed. All were of the same height (10 cm) and width (size perpendicular to the reach axis, 2.4 cm), similar in weight (48 g for the heaviest, 35 g for the lightest), made of wood and spray-painted matt black. Object 1: size parallel to the reach axis (D) = 2.4 cm; height of grasp surface (H) = 9 cm (grasp surface area = 21.6 cm²). Object 2: D = 2.4 cm; H = 2.4 cm (area = 5.76 cm²). Object 3: D = 0.2 cm; H = 9 cm (area = 1.8 cm²). Object 4: D = 0.2 cm; H = 2.4 cm (area = 0.48 cm²). Object 5: D = 2.4 cm; H = 0.2 cm (area = 0.48 cm²). Object 6: D = 0.2 cm; H = 0.2 cm (area = 0.04 cm²). For the four objects where the grasping target was not the full 9 cm high, the centre of the grasping target was placed 6 cm from the base of the target. This position corresponds (approximately) to the mid point of the position on the 9-cm target that subjects tend to place the thumb and index finger when grasping it (when given the choice).

Based on the area of the grasp surface targets alone, we might predict (in line with Fitts law in one dimension) that since the grasp target area increases in the (object) order 1 < 2 < 3 < 4 = 5 < 6 that the total movement times (MTs) for reaches directed at these six objects would be ordered in the same fashion. However, this prediction assumes that changes in D and H lead to the same change in accuracy constraint. There is, however, no reason to suppose that this is a valid assumption: since the finger pads have a greater

Methods

Subjects
Six individuals diagnosed as suffering from idiopathic Parkinson’s disease at early stage III, or lower, on the Hoehn and Yahr scale (see Table 1 for details) and six age-matched elderly individuals served as subjects. The elderly control subjects had all been previously screened for dementia and medical problems which could affect their movement control.
**Table 1** Parkinson's disease patient details

<table>
<thead>
<tr>
<th>Sex</th>
<th>Age (years)</th>
<th>Years since diagnosis</th>
<th>Medication</th>
<th>Side affected</th>
<th>Clinical signs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>L-Dopryl</td>
<td>Sinemet</td>
<td></td>
</tr>
<tr>
<td>(1)</td>
<td>M</td>
<td>59</td>
<td>1</td>
<td>1–0–0</td>
<td>Right</td>
</tr>
<tr>
<td>(2)</td>
<td>F</td>
<td>75</td>
<td>2</td>
<td>1–0–0</td>
<td>–</td>
</tr>
<tr>
<td>(3)</td>
<td>F</td>
<td>72</td>
<td>1</td>
<td>1–0–0</td>
<td>–</td>
</tr>
<tr>
<td>(4)</td>
<td>F</td>
<td>72</td>
<td>3</td>
<td>4–1–0</td>
<td>–</td>
</tr>
<tr>
<td>(5)</td>
<td>M</td>
<td>72</td>
<td>3</td>
<td>1–0–0</td>
<td>–</td>
</tr>
<tr>
<td>(6)</td>
<td>M</td>
<td>68</td>
<td>8</td>
<td>2–0–0</td>
<td>–</td>
</tr>
</tbody>
</table>

Medication: number of tablets morning–midday–evening (Sinemet: controlled release, *50 mg; † 125 mg and ‡ 250 mg; Permax 1 mg). Clinical signs: signs when medicated, according to examination at time of testing and self report: T = resting and/or postural tremor, R = rigidity, B = bradykinesia, A = akinesia, P = problems with static and dynamic upright posture, O = on–off phenomenon, F = freezing (‘+’ = both sides affected; ‘−’ = neither side noticeably affected; ‘l’ = left side mainly affected; ‘r’ = right side mainly affected). Patients 1 and 3 were in stage I of the disease, other patients were in stage II (Patient 2) or late stage II–early stage III (Patients 4, 5 and 6).

length (size along the finger) than width (size perpendicular to the line of the finger) a small H is expected to impose a rather greater constraint on accuracy than D of equal size, suggesting that the MTs should be ordered, $1 < 2 < 3 < 4 < 5 < 6$.

**Procedure**

Targets were placed a distance of 25 cm along the subject’s midline from the starting position and were displaced to the right of the midline by ~5 cm in the unimanual trials but not in the bimanual trials to avoid requiring subjects to make an awkward extension of the wrist. When the object was in the target position the subject was given a verbal signal by the experimenter to begin the reach (‘go’). On hearing this signal the subject was instructed to reach and grasp the target object with the thumb and index finger (unimanual) or with the two index fingers (bimanual trials) and raise it a few centimetres above the surface of the table before putting it down again and returning the hand (or hands) to the starting position (this was demonstrated to them by the experimenter for both unimanual and bimanual reaches). Subjects were told that they should reach at a comfortable pace which would be normal for picking up an object in the home and that a fast reaction to the go signal was not required. They were told that it was not necessary to place the target back exactly where it had been before they had picked it up and that the exact height to which they raised the object off the table was unimportant.

Subjects reached for each target a total of 12 times both unimanually and bimanually. The 12 trials for each object were grouped into two blocks of six and the unimanual and bimanual trials into two blocks of 36, the latter being made up of six blocks of six trials (one for each target object) in one of the 720 different possible orders (selected at random for each subject). Each subject performed a 36-trial block of unimanual trials, a block of bimanual trials, a block of unimanual trials and then the final block of bimanual trials (a total of 144 trials). Data was collected for a total of 3 s; collection was initiated by the experimenter at slightly before the ‘go’ signal was given. The inter-trial interval was variable and ranged between 1 and 5 s within blocks of trials. Between blocks of trials the interval could be longer as the target object needed to be changed. At the end of each 36-trial block there was a pause of 3–4 min as the markers were rearranged. All subjects received a total of at least 20 practice trials with the various target objects in both tasks (all subjects felt comfortable with the tasks given this amount of practice).

**Data analysis**

Data were first subjected to a residuals analysis (Winter, 1990) to determine the appropriate cut-off frequency for filtering. A cut-off of between 5 and 10 Hz was suggested by this analysis for both unimanual and bimanual data. The filtering was done by a dual pass through a second order Butterworth digital filter with a cut-off frequency of 12 Hz, equivalent to using a fourth order filter with no phase lag and a cut-off frequency of 9.63 Hz. Prior to filtering, trials in which there were missing data due to occlusion of the IREDs were subject to a procedure which interpolated information could be extracted from them) or were used only to derive the timing and magnitude of kinematic events (see below) which lay outside the missing segment(s) and which did not involve computation of the derivative of the original time series.

The transport component in the unimanual standard prehension task is usually thought to move the hand to the vicinity of the target object. In the case of the bimanual task the transport component moves both hands to the target object; in effect, it moves the aperture such that the fingers are either side of the target. It seems reasonable to suppose that it is the mid-point between the two fingers that is being
transported, such that it coincides with the mid-point of the
target grip opposition axis, i.e. that it is the grasp aperture
that is being transported, not the hand per se. Therefore, it
may be proposed that the mid-point between IREDs on the
two hands can be used to define the transport component. In
the experiments reported here we followed standard practice
by using a wrist IRED to define the transport component in
the unimanual task and, in an analogous fashion, the mid-
point between the two wrist IREDs was used to define the
transport component in the bimanual task.

The filtered x, y and z coordinates of the IREDs were used
to compute the following time series. Unimanual trials: (i)
aperture, the distance between the finger and thumb IREDs;
(ii) aperture speed, the numerical time derivative of aperture
time series; (iii) transport path length, the distance travelled
by the wrist IRED in 3D space, which is a sum of distances
between sequential positions of the IRED; and (iv) transport
tangential speed, the square root of the sum of the squares
of the numerical derivatives of the x, y and z coordinates of
the wrist IRED. Bimanual trials: (i) grasp (finger) aperture,
the distance between knuckle IREDs and its numerical time derivative; (ii) knuckle aperture, the distance
between knuckle IREDs and its numerical time derivative;
(iii) wrist aperture, the distance between wrist IREDs and its
numerical time derivative; (iv) transport path length, the
distance travelled by the mid-point between the two wrist
IREDs in 3D space (sum of distances between sequential
positions of the mid-point position); (v) transport tangential
speed, the tangential speed of the wrists’ mid-point position;
(vi) tangential speed, right wrist; and (vii) tangential speed,
left wrist.

The timing and magnitude of various events were derived
from the above time series: (i) onset of movements [estimated
from the time series using an automatic algorithm
recommended by Teasdale et al. (1993)] as follows: (a)
locate the sample (sample 1) at which the time series first
exceeds 10% of its maximum value ($V_{max}$); (b) working back
from this point stop at the first sample (sample $S$) which is
$\approx \lceil(V_{max}/10) - (V_{max}/100)\rceil$; (c) find the standard deviation
of the series between sample 1 and sample $S$ (SD); (d)
working back from sample $S$, stop at the first sample which
$\approx (sample S - SD$, this is the onset); (ii) speed and maximum
aperture size and their times of occurrence; (iii) movement
offset (using the same algorithm as for onsets on the time-
reversed aperture time series); and (iv) MTs (difference
between offset and onsets). A normalized integrated jerk
measure was also computed for the transport path length and
grasp aperture time series to quantify movement smoothness
cf. Flash and Hogan, 1985). Overall group and task
differences in these and the derived measures were analysed
for statistical reliability using 2 × 2 (Group × Task) split-
plot analysis of variance (ANOVA) with a logarithmic
transformation to equate variances where necessary. Jerk ($J$)
was computed numerically as the third derivative of path
length (i.e. the time series of distance travelled along the
movement path, which is a scalar quantity and improves jerk
as a measure of smoothness by reducing the confound
between the shape of a trajectory from its smoothness which
is present for jerk, defined in terms of a position vector in
3D space). Jerk scores were computed as the square root of
the normalized integral of jerk squared, a dimensionless
smoothness measure independent of movement duration and
amplitude (Teulings et al., 1997; Kitazawa et al., 1993).

Jerk score = $\alpha(1/2)[\int J^2 dt \times (duration)^2/(total path length)]^2$.

The portions of the various time series between computed
movement onset and offsets were linearly time-normalized
to 500 samples using cubic spline interpolation. From the
normalized time series, means and standard deviations were

calculated and used to display the paths of the IREDs through
3D space. Although means and standard deviations for
each sample can sometimes provide a useful picture of
performance, the description provided is necessarily rather
restricted. A more complete and potentially insightful
description of the form of the data is provided by the
Kahunen–Loeve eigenvector transformation or principle
components analysis (PCA). Each time series is an ordered
list of numbers and can therefore be treated as a vector. PCA
finds a set of orthonormal basis vectors for a set of vectors
and orders these according to the amount of variance in the
original data set they account for (these are the eigenvectors
of the covariance matrix of the complete data set). If $n$ basis
vectors ($P_1, \ldots, P_n$) are needed to account for 100% of
the variance in the original data set, then any vector in the
original set $D_k$ can be expressed exactly as a weighted sum
of these $n$ basis vectors:

$D_k = a_0 + a_1P_1 + a_2P_2 + \ldots + a_nP_n$

where $a_0, \ldots, a_n$ are scalar constants. PCA was performed
on the set of time-normalized aperture size, transport tangential
speed and path length time series obtained for each subject
in the unimanual and bimanual tasks.

Results

General description of performance (PCA)

Figure 1 shows the mean spatial paths (solid lines) ± SD
dotted lines) of the unimanual (A) and bimanual (B) reach-
to-grasp movements in the plane of the table for one subject
from each group. These plots illustrate the general finding
that both groups of subjects generated basically similar spatial
paths in both types of reach-to-grasp movements. To describe
the transport and grasp components of the actions we used
PCA as described in the methods.

The PCA revealed that the complete data sets from each
subject were well described by the first three principle
components (PCs) which account for ≈99% of the variance
in the data sets. Table 2 presents the mean proportion of
variance in the aperture, tangential speed and transport path
length data sets for the two groups of subjects accounted for
by the first, second and third PCs (the range is also given).
Fig. 1 Spatial paths in the plane of the table from a control subject and a patient with Parkinson’s disease. (A) Mean (continuous) ± 1 SD (dotted) positions of the wrist, finger and thumb markers relative to the optotrak calibration frame of reference for unimanual reaches-to-grasp by Control 2 (left) and Patient 2 (right). (B) A similar plot of the left and right wrist and left and right index finger markers for bimanual reaches-to-grasp by the same subjects.

Table 2 Mean percentage of variance accounted for by the first, second and third principle components (PC1–C3) derived from the analysis of the aperture, tangential speed and transport path-length data sets from the two groups of subjects

<table>
<thead>
<tr>
<th>Data set</th>
<th>Control group</th>
<th>Parkinson’s disease group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PC1</td>
<td>PC2</td>
</tr>
<tr>
<td>Unimanual task</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aperture</td>
<td>92.54</td>
<td>4.9</td>
</tr>
<tr>
<td>Path</td>
<td>98.85</td>
<td>1.0</td>
</tr>
<tr>
<td>Speed</td>
<td>90.44</td>
<td>7.4</td>
</tr>
<tr>
<td>Bimanual task</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aperture</td>
<td>90.92</td>
<td>7.3</td>
</tr>
<tr>
<td>Path</td>
<td>97.51</td>
<td>2.2</td>
</tr>
<tr>
<td>Speed</td>
<td>93.61</td>
<td>5.6</td>
</tr>
</tbody>
</table>

The first PC captures the most variance in the data set and is very close in shape to the mean function. The second and third PCs capture the bulk of the variance remaining after the first PC has been removed and therefore provide a description of the variability in the data. Figure 2 shows the first (left), second (middle) and third (right) PCs obtained from the analysis of the aperture time series from the two tasks in the two groups of subjects (all the first PCs are shown). The pattern is basically the same for all subjects and similar for the two tasks. Note that the second PC in each case has a form very similar to the derivative to the first component; this means that the variation is maximal approximately when the speed is greatest (a feature that has been commented on in other movement data (e.g. Ramsay, 1982; Paulignan et al., 1990). Note, further, that for both groups the peak aperture tends to occur relatively early in the bimanual task and that the peak apertures occur later in the Parkinson’s disease patients (this effect is analysed further below).

Figure 3 shows the first PCs derived from the aperture data sets, for each subject, plotted as a function of the first PCs derived from the corresponding transport path-length data sets (scaled from 0 to 1). This ‘spatial plot’ (Haggard and Wing, 1991) conveniently displays how the aperture (grasp component) develops as a function of the distance it has travelled towards the target (transport component) and is consequently a depiction of the concurrent execution of the two components. These plots accentuate a feature of the data displayed in Fig. 2: performance of the unimanual task in the control group is characterized by an initial relatively fast opening of the aperture followed by a slower phase, a pattern which is absent in the Parkinson’s disease patients and in performance of the bimanual task. This two-phase pattern of aperture opening is also observed in young subjects (Tresilian and Stelmach, 1997) and may be due to the fact that the starting posture in the unimanual task is such that the first interphalangeal joint of the index finger is ~60–70% extended (has ~30° of extension available), whereas the second interphalangeal joint is almost fully flexed (has ~80° of extension available). Both joints are initially extending together then the first interphalangeal meets a mechanical stop and the second interphalangeal continues on its own. No similar constraints are present in the bimanual task. The absence of the fast initial phase of unimanual opening in the Parkinson’s disease patients may be interpreted as due to their having to work against flexor rigidity when opening the aperture, which leads them to open more slowly and with a longer delay than normal. They show no similar slowing in bimanual task, in which initial aperture opening is performed largely by adduction of the shoulders.

We decided to examine whether earlier findings concerning delayed onset of aperture opening relative to onset of transport movement for Parkinson’s disease patients performing the standard prehension task (Castiello et al., 1993) were replicated. Box plots of the onset difference data for individual subjects in the two groups are presented in Fig. 3C. The
Fig. 2 Principle components (PCs) from the analysis of the complete unimanual (upper) and bimanual (lower) aperture-size data sets of individual subjects in (A) control subjects; (B) Parkinson’s disease patients. First PCs from all subjects are shown on the left; to avoid clutter, second (middle) and third (right) PCs from only three control subjects and four Parkinson’s disease patients are shown (those obtained from analysis of the other subjects were similar to those shown).
difference between the means for each group was statistically analysed using a $t$ test (performed on the logarithms of subject means to equalize the group variances) and was significant ($t = -1.92, P < 0.05$, one-tailed), the mean difference in onset between groups was 40 ms. However, as can be seen from Fig. 3, the distributions of onset-difference data from individual Parkinson’s disease patients is skewed towards zero, and the mean is not a good measure of central tendency in their data (though it is for the control data). If we take the medians as a measure of central tendency, the average difference between groups drops to 13 ms and is not statistically significant using the same analysis procedure ($t = -0.97$). Thus, the Parkinson’s disease patients open their finger–thumb apertures slower than the control subjects (cf. Figs 1 and 3) and their aperture–transport onset difference has a greater spread towards larger values than is characteristic of the control subjects, but there is little systematic

![Fig. 3](image-url)

**Fig. 3** First PCs of aperture size plotted as a function of the first PC of transport path length for each subject in both groups (left, control subjects; right, Parkinson’s disease patients): (A) unimanual task; (B) bimanual task. Box plots (C) show the difference between the onset of the transport movement and the onset of the aperture formation movement for both groups of subjects in the unimanual task.
Stability of reaching-to-grasp

Fig. 4 Movement times. Individual subject (dotted) and overall mean (continuous) movement times from the unimanual (A) and bimanual (B) tasks for each target object (control subjects on the left; Parkinson’s disease patients on the right). Error bars indicate the standard error of the mean. (C) Group mean MTs plotted as a function of the logarithm of the target grasp surface area (A) for the five different areas used in this study. Continuous lines and closed symbols = unimanual task; dotted lines and open symbols = bimanual task. Results of linear regressions are shown (**P < 0.01; ***P < 0.001).
indication that the central tendency of Parkinson’s disease patients was biased towards an appreciably longer delay.

This analysis of the data indicates that the fundamental pattern of performance of the two groups of subjects is similar in the two tasks. There are clear indications that the Parkinson’s disease patients make less smooth movements as the residual variance in the data sets, once the dominant mode (first PC) has been removed, is described by much more irregular functions in this group than in control subjects. In what follows, a more detailed analysis of the similarities in the pattern of performance and the differences in detail between the two groups will be provided.

**Dependence of movement parameters on target object characteristics**

**Transport movements**

Figure 4 shows the mean MT (error bars indicate the standard error) for reaches to each target for individual control subjects (left) and Parkinson’s disease patients (right). In all subjects in both tasks there is a visible trend for MT to increase as target accuracy constraints increase: there was a significant trend for MT to increase in the (task) order 1 < 2 < 3 < (4+5)/2 < 6 in both groups in the two tasks as assessed by Page’s L test (unimanual task, control subjects, L = 312, P < 0.01; unimanual task, Parkinson’s disease patients, L = 310, P < 0.01; bimanual task, control subjects, L = 316, P < 0.01; bimanual task, Parkinson’s disease patients, L = 318, P < 0.01). This pattern conforms to Fitts’ law as demonstrated in the bottom panels of Fig. 4 in which the group mean MTs are plotted against the logarithm of the grasp surface area (A) of the target objects (Objects 4 and 5 have the same area and their MTs were averaged): Fitts’ law predicts a linear relationship between MT and log(A) and this is confirmed in both groups (results of linear regressions are given in the figure; all were statistically significant and accounted for well over 90% of the variance).

It was expected that the Parkinson’s disease patients would have longer MTs and reach smaller maximum speeds reflecting their bradykinesia; this effect is evident in Fig. 4. A split-plot ANOVA was used to assess whether the mean differences (collapsed across target objects) between groups and between tasks on the MT variable were statistically reliable: the Parkinson’s disease group took significantly longer than the control group [F(1,9) = 8.81, P = 0.016]; there was no significant effect of Task [F(1,9) = 2.88, P = 0.124] and no significant Task×Group interaction [F(1,1) = 1.1, P = 0.32]. The effect size (ES) of the group difference in MT can be calculated as: ES(MT) = (mean MT in patients – mean MT in control subjects)/SD of MT in control subjects). When there are <20 subjects it is usual to correct the ES by multiplying by the factor \[1 - 3/(4(N - 1) - 9)]\], where N is the number of control subjects (Hedges and Olkin, 1985). The overall ES(MT) computed in this way was 4.0 (the difference between the group means was 400 ms) for the unimanual task and 5.72 (difference in means, 392 ms) for the bimanual task; an ES >0.8 is considered large (Cohen, 1988).

The overall mean maximum tangential speed data for the six subjects reaching for the different targets is shown in Figure 5A show the mean maximum speeds for the two groups in the two tasks. The control subjects (left) reach higher speeds than the Parkinson’s disease patients (right) and higher speeds are reached in the unimanual task than in the bimanual task. These effects were analysed using ANOVA on the mean data for each subject collapsed across target objects (control group means ± SDs: unimanual task, 788.0 ± 5.61 mm/s; bimanual task, 700.1 ± 13.03 mm/s and Parkinson’s disease group means ± SDs: unimanual task, 580.7 ± 29.8 mm/s; bimanual task, 508.3 ± 11.4 mm/s). The Parkinson’s disease patients reached significantly lower maximum speeds [F(1,9) = 636, P < 0.0001] and significantly greater maximum speeds were reached in the unimanual task [F(1,9) = 164, P < 0.0001]; there was no significant Group×Task interaction [F(1,1) = 1.55]. The group maximum tangential speed ES was 27 for the unimanual task and 10.8 for the bimanual task.

Figure 5B shows the overall mean relative and absolute times to maximum tangential speed for reaches to the six targets in the two tasks. The left panel of Fig. 5B shows that there is a tendency in control subjects for the relative time to maximum speed to decrease as target accuracy constraints increase, while the absolute time to maximum speed remains constant. In other words, there is a tendency for the deceleration phase of the transport movement to get longer as accuracy constraints increase. The control subjects decreased relative time with maximum speed as MT increased in response to increasing accuracy constraint: correlations of mean relative time to maximum speed and movement time were statistically significant for all subjects in the unimanual task (mean r = –0.84, SD = 0.25). In the bimanual task, correlation coefficients were smaller on average (mean r = –0.65, SD = 0.28) and only two were statistically reliable (all correlation coefficients in both tasks had the same sign). Parkinson’s disease data shows a less clear picture. Correlations of individual subject mean MTs and relative times to maximum speed yielded coefficients that varied in sign from subject to subject (unimanual task, range –0.93 to +0.26; bimanual task, range –0.97 to +0.74), the magnitude of the correlation coefficients was smaller on average than control subjects (unimanual task, mean = 0.4, SD = 0.34; bimanual task, mean = 0.59, SD = 0.30) and only two in total were statistically reliable.

The Parkinson’s disease patients, on the other hand, showed a much less systematic picture: Patients 2 and 6 actually showed a tendency to increase relative time to maximum speed as MT increased (positive correlation, though the slopes of the regression lines were always <0.1: if the MT increased by 1 s the maximum speed would occur <100 ms later). It is possible that the Parkinson’s disease patients were adopting a different strategy from the control subjects,
decreasing maximum speed rather than increasing the deceleration phase. However, only Patient 6 in the unimanual task showed a systematic tendency to decrease speed to increase MT. As a group, the Parkinson’s disease patients show no systematic tendency either to increase the length of the deceleration phase or to decrease maximum speed in order to increase MT.

**Grasp formation movements**

Figure 6 shows the mean relative time to maximum grasp aperture for reaches to each target organized in the same way as for MT. With the exception of Patient 6, there are three clear tendencies illustrated in this figure: first, maximum aperture is reached relatively early in the bimanual task. Secondly, there is a visible trend for this relative time to decrease as the target accuracy constraint increases. This trend was statistically reliable for the control group in both tasks (unimanual task, $L = 312, P < 0.01$; bimanual task, $L = 316, P < 0.01$). For the Parkinson’s disease group it was only reliable in the unimanual task ($L = 300, P < 0.05$). Thirdly, the Parkinson’s disease patients tend to reach time to maximum aperture relatively late than the control subjects in the unimanual but not the bimanual task (interaction between Group and Task). ANOVA revealed that the difference in relative timing between the two tasks was significant [$F(1,9) = 42.14, P < 0.001$], that the interaction was marginal [$F(1,1) = 4.35, P = 0.067$] and that there was no overall difference between the two groups [$F(1,9) = 3.06, P = 0.114$].

The pattern of relative timing translates into the following pattern for the absolute time spent in the enclose phase (enclose time) of the grasp component. For the control group the mean enclose times collapsed across target objects were 322 ms (range 205 – 462 ms) for the unimanual and 469 ms (range 283 – 664 ms) for the bimanual task. For the Parkinson’s disease group the means were 295 ms (range 91 – 708 ms) and 675 ms (range 376 – 1130 ms) respectively. A similar ANOVA analysis to that carried out on the relative timing data (taking logarithms to equate variances) showed there were no overall group differences [$F(1,9) = 0.1$], a significant effect of Task [$F(1,9) = 53.12, P < 0.0001$] and a significant Task $\times$ Group interaction [$F(1,1) = 10.95, P < 0.01$]. The trends in MT and relative time to maximum aperture imply a longer enclose phase as accuracy constraints increase. The absolute time spent in the enclose phase increased quite notably from Object 1 to Object 6; for the Parkinson’s disease group the mean increases for individual
patients were (in order of patient number) 244, 91, 152, 171 and 160 ms in the unimanual task and 105, 118, 205, 31, 105 and 216 ms in the bimanual task. In the control group the increases were 66, 76, 60, 58, 223 and 214 ms in the unimanual task and 59, 107, 220, 74, 227 and 157 ms in the bimanual task.

It was found that, for each target condition, the relative time to peak aperture and to maximum speed on individual trials tended to be correlated for both groups. The overall group mean correlation coefficient for the two tasks summarize the general trend quite well; the mean for both tasks was the same (to two decimal places) for the Parkinson’s disease patients ($r = 0.68, 73\% \text{ statistically significant}$ in the unimanual task, $67\%$ in the bimanual task) but different for the control subjects (unimanual $r = 0.48, 36\%$ significant; bimanual $r = 0.64, 67\%$ significant). Analysis of the mean correlation coefficients for each subject using ANOVA showed a significant overall difference between groups [$F(1,9) = 23.85, P < 0.001$; the Parkinson’s disease group had significantly larger correlation coefficients, a significant difference between tasks [$F(1,9) = 11.61, P < 0.01$; the correlations were higher in the bimanual task] and a significant Task × Group interaction [$F(1,1) = 6.71, P < 0.05$] indicating that there was a difference between the two tasks only in the control group.

The size of the maximum aperture tended to be larger in the bimanual task than the unimanual task in both groups of subjects, an effect which was statistically reliable as assessed

Fig. 6 Relative time to maximum aperture. Individual subject (dotted) and overall mean (continuous) relative times to maximum grasp aperture from the unimanual (A) and bimanual (B) tasks for each target object (control subjects on the left; Parkinson’s disease patients on the right). Error bars indicate the standard error.
by a split plot ANOVA performed on the means collapsed across target objects; there was a significant difference between tasks \(F(1,9) = 29.89, P < 0.01\) but no significant difference between groups \(F(1,9) = 0.67\) [the Group×Task interaction was not significant, \(F(1,1) = 0.62\)]. There was no tendency for maximum aperture to be systematically influenced by the target accuracy constraints in any subject.

**Movement smoothness**

Movements of the Parkinson’s disease group were jerkier than the control group. In both groups the aperture formation movements tended to be jerkier than the transport movements and there was no systematic change in jerk with target object. For the bimanual task the overall mean transport jerk was 594 (range 141–2253) for the Parkinson’s disease group and 102.7 (range 72–134) for the control group. The mean aperture jerk was 1587 (range 496–4887) for the Parkinson’s disease group and 588 (range 434–786) for the control group.

Note that the normalized jerk score for a minimum jerk trajectory (Flash and Hogan, 1985) between two points is 3.7. The individual subject means (collapsed across target objects) for the transport and aperture jerk in the two tasks were analysed with separate split-plot ANOVAs (the means were first subjected to a logarithmic transformation since the between-subjects variance was proportional to the mean). The effect of Group was statistically significant for both measures [for transport \(F(1,9) = 5.44, P < 0.05\); for aperture \(F(1,9) = 9.2, P < 0.025\)] and the unimanual aperture jerk was significantly higher than that of the bimanual aperture jerk \(F(1,9) = 11.38, P < 0.01\) though there was no reliable difference in the transport jerk between the two tasks \(F(1,9) = 2.99, P = 0.118\). The interactions were not significant. The higher jerk of the Parkinson’s disease group was evident from visual inspection of their speed profiles: profiles from the Parkinson’s disease patients were much less smooth than those from the control subjects. Patient 6 was especially uneven and this was similar on every trial for this patient, suggesting the existence of an action tremor (see Fig. 2).

**Bimanual performance**

Do Parkinson’s disease patients show evidence that they are using fewer degrees of freedom in the bimanual task?

To examine this question, we decided to study how the wrist, knuckle and finger apertures developed over time. If the maxima of these apertures occur at different times but nevertheless preserve a fixed order then there is evidence that the degrees of freedom, particular to wrist aperture (shoulder rotation and/or abduction/adduction), knuckle aperture (wrist flexion/extension) and finger aperture (finger flexion/extension) are all being used.

For the control subjects, the maxima of the three bimanual apertures were invariably ordered in time with the maximum wrist aperture occurring first, on average 88 ms before the maximum knuckle aperture which occurred 97 ms before the maximum grasp (finger) aperture. The same pattern was also observed in the Parkinson’s disease patients, maximum wrist aperture 159 ms before maximum knuckle aperture, which was 111 ms before maximum grasp aperture. This ordering was not merely observed on average; for both groups it was observed on virtually every trial (there was a total of only nine trials for the control group in which either maximum wrist aperture occurred after maximum knuckle or maximum knuckle occurred after maximum finger; there were eight such trials for Patients 1–5). The sole exception was Patient 6 who tended to reach the three peak apertures at approximately the same time.

If only the shoulder degrees of freedom are being used for aperture formation then the evolution of aperture over time should be the same for all three apertures; if the shoulder and wrist are being used then the knuckle and finger aperture development should be the same and different from the wrist; if all three are used then the evolution of all three apertures should be different. Figure 7 illustrates these expectations for three of the Parkinson’s disease patients and three of the control subjects; the mean size of all three apertures is shown plotted as a function of normalized time (thick lines) and the mean speed of the apertures (thin lines) is also shown. It is clear that the aperture-size curves follow the patterns of Fig. 7: the wrist-aperture curves are different from the knuckle and finger apertures, the latter are quite similar for most subjects (e.g. Controls 2 and 3 and Patient 3) and differ most for Patient 1 and Control 1. Patient 6 is the exception; the wrist, knuckle and finger apertures all develop over time in almost exactly the same way, and there is little wrist flexion/extension and almost no functional index finger flexion/extension. The differences are perhaps more evident in the aperture-speed curves: peak opening and closing speeds are different and are reached at different times for the three apertures with the exception of Patient 6 (Fig. 7).

We explored the possibility that the number of degrees of freedom contributing to aperture formation depends upon the task difficulty (as assessed by the grasp surface area of the target object) with a more rigid strategy (fewer functional degrees of freedom) being employed by Parkinson’s disease patients when the grasp surface area was greater. The grasp area was greatest for Object 6 and least for Object 1 and results reported above demonstrate that reaches to Objects 1 and 6 showed differences consistent with increased grasp area for all subjects. We considered the relative times to the different apertures for reaches to Objects 1 and 6 by Patients 1–5, with the expectation that if the coordinative abilities of these patients were particularly affected by the more demanding Object 6, the peak apertures should occur closer in time for this object than for Object 1. There was no evidence that this was the case; for example, the mean difference in the relative times to peak knuckle and finger apertures for the five patients were very close for the two
objects, in fact the mean difference was larger (in four patients) for reaches to Object 6 than for those to Object 1, the reverse of the prediction [overall means: 142 ms (range 71–187 ms) for Object 6; 118 ms (range 55 – 185 ms) for Object 1]. Moreover, peak knuckle and wrist apertures for reaches to Object 1 were reliably correlated \((P < 0.05)\) in Patients 1, 2, 3 and 5 \((r = 0.74, 0.81, 0.87 \text{ and } 0.83, \text{ respectively})\) but not for reaches to Object 6 \((r = 0.02, 0.55, 0.28 \text{ and } 0.32, \text{ respectively}; \ P > 0.1)\). Patient 4 was the exception, times to these peak apertures were reliably correlated in reaches to Object 6 \((r = 0.85, n=10, P < 0.01)\) but not in reaches to Object 1 \((r = 0.47, n=12)\). These results suggest that these Parkinson’s disease patients were using finger flexion/extension and that this degree of freedom (component) was being used somewhat more independently in the reaches to Object 6 than in reaches to Object 1 (with the exception of Patient 5).

**Symmetry of left and right limb movements**

The movements of the left and right limbs were spatially very symmetric for both Parkinson’s disease patients and the control subjects. Differences between the movements of the left and right limbs were quantified by the following

---

**Fig. 7** Mean time-normalized aperture (thick lines) and aperture speed (thin lines) profiles for selected control subjects (left) and Parkinson’s disease patients (right). C1–3 from Controls 1–3 and P3, P5 and P6 from Patients 3, 5 and 6.
measures. (i) The movement onset asynchrony (difference in onset times of the left and right wrists). (ii) The difference in the maximum tangential speed of the two wrists and the difference in the time of occurrence of these maxima. (iii) The area between the path swept out by the mid-point of the two wrist markers in the plane of the table and the straight line joining the start and end positions of this mid-point (straightness error). If the left and right limb movements are perfectly symmetrical the straightness error should be zero. (iv) The area between the paths swept out by the left and right wrist markers in the plane perpendicular to the table (height difference error). Again, perfectly symmetrical movements would result in a zero height difference error. (v) The normalized jerk measure computed for the left and right wrists.

All subjects performed rather symmetrically and the only measures on which there were any observable and systematic differences were onset asynchrony [three Parkinson’s disease patients (Patients 2, 3 and 6) showed considerably more variability than any of the control subjects] and jerk (see Fig. 8, top and bottom panels). The straightness errors, for example, were very small (Fig. 8, middle panels). For comparison, if the start- and end-points of a movement are 20 cm apart and joined by a circular arc (radius 26 cm) which is has a maximum distance of 2 cm from the straight line joining the two points, the straightness error (the area bounded by the straight line and the arc) is 27 cm². The differences in the magnitudes of these errors between Parkinson’s disease and control subjects are negligibly small and not systematic as is immediately obvious from Fig. 8. What is also obvious from the figure is that the wrist straightness error is systematically larger than the finger straightness error with two exceptions: Patients 5 and 6 had similar straightness errors for the wrist and the finger. This is consistent with the finding that Patient 6 did not move the fingers relative to the wrist as described above.

Figure 8C shows the mean difference in the normalized jerk measure between the left and right wrists for all subjects. Note that for three of the Parkinson’s disease patients (Patients 3, 4 and 6), the mean jerk of the two limbs tends to differ markedly but is very similar in all the control subjects with the exception of Control 6 (whose mean is nevertheless smaller than any of the asymmetrical Parkinson’s disease patients). All subjects, with the exception of Patient 4 showed
a significant positive correlation between the jerk scores of the two limbs at least the 0.05 probability level [for the control subjects, mean $r = 0.64$ and mean slope = 0.68; for the Parkinson’s disease patients (excluding Patient 4), mean $r = 0.69$ and mean slope = 0.81]. Patient 4 showed a non-significant ($P = 0.081$) slightly negative correlation ($r = -0.21$), the slope of the regression line was ~0.002.

**Discussion**

In both reach-to-grasp tasks, the Parkinson’s disease patients clearly demonstrated two non-specific movement impairments characteristic of the disease; they moved more slowly, taking ~30% longer to complete the movement and reaching peak speeds ~25–30% below those in control subjects (the associated effect sizes were very large) and their movements were considerably less smooth, producing jerk scores about twice those of the control subjects. At coarse spatial and temporal resolutions the transport and aperture development movements generated by the two groups of subjects were very similar. This was clear from the PCA of the transport and aperture-formation data sets and also from the averaged time series shown in Figs 1 and 7. There was little indication that the Parkinson’s disease patients displayed any differences at a coarse resolution in their trajectory formation and trajectory variability; the form of the two dominant modes of variability in the data (second and third PCs) were similar in the two groups. At fine spatiotemporal resolution the subjects in the two groups were rather different; the trajectories of the control group were relatively smooth whereas those of the Parkinson’s disease group were rather irregular, and there was clear evidence of small-scale fluctuations in position and speed (possibly a manifestation of an action tremor in some subjects) which led to significantly higher jerk in the movements of the Parkinson’s disease group. Moreover, it is clear from Fig. 4 that the Parkinson’s disease patients’ speed of aperture opening relative to arm transport in the unimanual task is different from the control subjects, whereas it is similar in the bimanual task.

These differences show that the movements of the Parkinson’s disease patients in this experiment were impaired in the tasks investigated. It is important to establish this before proceeding further with any analysis since Connor and Abbs (1991) have argued that the somatotopic organization of the basal ganglia means that the impairments seen in Parkinson’s disease can be body-part specific and they have presented evidence that this occurs. Our subjects showed systematic impairment of upper limb movement in both proximal (arm) and distal (hand and fingers) segments, so we have demonstrated that their impairment affects the effector systems being used in our tasks. Nevertheless, despite the obvious impairments, the basic patterns of performance of the Parkinson’s disease group was very similar to that of the control group. These patterns may be summarized as follows. (i) Maximum transport tangential speeds were smaller in the bimanual task and occurred later in the movement. The average speeds were similar in the two tasks since the MTs were not appreciably different. (ii) Time of maximum aperture occurred earlier in the bimanual task, thus there was a longer enclose phase for the grasp component. (iii) Maximum aperture was larger in the bimanual task by ~20%. (iv) In both tasks MT increased as target accuracy constraints increased in a manner which conformed to Fitts’ law; a similar result with Parkinson’s disease patients was obtained by Halsband et al. (1990), who reported that the slope of the relationship was greater for the Parkinson’s disease as we found in this study (see Fig. 4). In addition, the time spent in the enclose phase of the grasp formation movement also increased with target accuracy in both groups, responses that have previously been reported for reaching-to-grasp in normal populations (e.g. Marteniuk et al., 1990; Jakobsen and Goodale, 1991; Castiello et al., 1993; Bootsma et al., 1994). (v) Variability in the relative timing of maximum transport speed in individual trials to particular target objects was reliably correlated with the variability in the timing of maximum aperture; if maximum speed occurred relatively early on a particular trial then so did maximum aperture. (vi) PCA revealed that the transport and aperture development time series functions for the complete set of trials by each subject could be accuracy represented by a linear combination of three basic functions (PCs). The average tendency in the time series (first PC) was similar in the two tasks, as was the structure of the residual variability (second and third PCs). (vii) The movements of the two limbs in the bimanual task were very symmetric and there was a systematic pattern of aperture development; wrist aperture reached its maximum first, then knuckle aperture and finally finger (grasp) aperture, indicating independent functional roles for the wrist and finger in grasp aperture formation. We found no systematic indication that Parkinson’s disease patients used fewer degrees of freedom/components. It is clear that the wrist and finger degrees of freedom are redundant in the bimanual task and could be frozen (as with Patient 6) if necessary. However, this patient was alone in failing to use the wrist and finger independently. It is notable that it was this patient who showed the most significant impairment of movement execution, he had longer MTs than any other subject and showed evidence of a pronounced action tremor.

Despite the basic similarities in the pattern of performance there were two notable differences between the performance of the two groups in addition to the patients’ relative slowness and jerking.

First, the total time to grasp and enclose was similar for both groups in the unimanual task but the Parkinson’s disease group showed a tendency to reach maximum aperture relatively late in the movement, since their MTs were greater, so they compensated with a shorter relative time to enclose. In the bimanual task the relative timing was the same in the two groups but the greater movement times of the Parkinson’s disease group meant that the total time to grasp and enclose was greater for this group (~200 ms greater on average).

Secondly, the subjects in the control group were
been found to be characteristic of both young and elderly subjects (e.g. Cooke et al., 1989; Darling et al., 1989; Marteniuk et al., 1990). There were indications of a tendency to decrease the maximum speed as well, but this was not systematic across subjects. The Parkinson’s disease group showed little systematic tendency to increase MT either by decreasing maximum speed or extending the duration of the deceleration phase. Parkinson’s disease patients were clearly able to modulate MT, but none of them was achieving this modulation in a systematic fashion on a trial-by-trial basis (with the exception of Patient 6 who was systematically decreasing maximum speed). This is consistent with other work which has shown that Parkinson’s disease patients have problems modulating movement speed and the timing of maximum speed in response to changing target accuracy constraints (e.g. Draper and Johns, 1964). It is not, however, consistent with the work of Inzelberg et al. (1990) who reported that the increase in MT in Parkinson’s disease is accompanied by a considerable asymmetry of the acceleration and deceleration phases, mostly due to a prolongation of the deceleration phase. The result of Inzelberg et al. (1990) is consistent with hypometric movements often observed in Parkinson’s disease in which the target position is undershot and additional submovements are required to reach the target; there was no systematic evidence for hypometric movement in our subjects which may be due to the fact that they were under medication and in relatively early stages of the disease.

The results presented here and in other studies of reaching-to-grasp in Parkinson’s disease patients (Müller and Stelmach, 1992; Castiello et al., 1993; Saling et al., 1996) demonstrate that the pattern of concurrent execution of the two component tasks in reach-to-grasp actions is similar to that observed in control subjects. Although Parkinson’s disease clearly impairs movement execution in these tasks it does not significantly affect the way the grasp aperture develops and the concurrent movement of the hand(s) to the target object. It may be proposed that the disease does not affect the established motor programmes organizing movement execution directly, rather these motor programmes operate in the context of a motor execution system whose controllability is degraded by the presence of pathological activity. Wichmann and DeLong (1993) recently concluded that all major abnormalities of Parkinson’s disease can be explained as a consequence of ‘increases in tonic and phasic activity in the basal ganglia–thalamocortical ‘motor’ circuit’ (p. 59). We would suppose that these increases in activity do not represent direct effects of the disease on well-learned motor programmes; rather they limit the ability of central motor control systems to generate appropriately modulated descending commands predictably, and they give rise to pathological descending signals which produce tremor and rigidity. This hypothesis predicts that well-learned motor tasks will be executed with much less skill by Parkinson’s disease patients, but that the basic patterns of performance (e.g. relative timing invariances, Fitts’ law characteristics, coordination between different component tasks) will be preserved and this is basically what has been found in prehension tasks both in this study and in others (Castiello et al., 1993; Saling et al., 1996).

Conclusions
It is often argued that there is an effector-independent level of programming in human movement control (e.g. Bernstein, 1967; Saltzman, 1979; Schmidt, 1980). Such effector independence is implied in many models of prehension (e.g. Hoff and Arbib, 1993) and there is empirical evidence that such a level is operative in human prehension (Wing and Fraser, 1983; Flanagan and Tresilian, 1994; Tresilian and Stelmach, 1997). In the study by Tresilian and Stelmach (1997), the bimanual task used was the same as that described above, and performance of healthy young subjects was compared with their performance on the standard unimanual task. A basic similarity in patterns of performance of the two tasks was observed and is evidence of an effector-independent organization for the coordination of concurrent reaching and grasping. This essential similarity was also a characteristic of the performance of the two groups of subjects in the experiment reported here. We were unable to find any evidence of changes in the coordination pattern in the two tasks or in the ways in which movements were adapted to increasing accuracy demands, despite significant movement impairment in the Parkinson’s disease group. We would conclude that the effector-independent level of motor programming responsible for transport–grasp coordination and movement accuracy adaptations is unaffected by Parkinson’s disease. Furthermore, increasing the number of degrees of freedom which need to be controlled does not necessarily compromise execution of a motor programme; the Parkinson’s disease group were quite capable of using the generalized reach-to-grasp motor programme to control an increased number of muscle/joint level degrees of freedom without an associated increase in performance deficits.

Acknowledgement
Support for this work was provided by NINDS grant NS17421 awarded to G.E.S.

References


Benecke R, Rothwell JC, Dick JPR, Day BL, Marsden CD. Simple and complex movements off and on treatment in patients with...


Teulings HL, Contreras-Vidal JL., Stelmach GE. Adler CH. Parkinsonism reduces coordination of fingers, wrist and arm in fine motor control. Exp Neurol 1997; 146: 159–70.


Received November 14, 1996. Revised May 22, 1997. Accepted June 2, 1997