Pergamon

Neuropsychologia, Vol. 32, No. 11, pp. 1367–1382, 1994

0028-3932/94 $7.00+0.00

0028-3932(94)00069-7

PARKINSON'S DISEASE: REORGANIZATION OF THE REACH TO GRASP MOVEMENT IN RESPONSE TO PERTURBATION OF THE DISTAL MOTOR PATTERNING

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(*Received* 12 *February* 1994; *accepted* 29 *April* 1994)

Abstract—This study assessed the kinematic changes to the reach to grasp movement in response to a perturbation of object size in 15 Parkinson's disease (PD) and 15 control subjects. For non-perturbed trials subjects reached 35 cm to grasp and lift either an illuminated small (0.7 cm) or large (8 cm) diameter cylinder. For perturbed trials (20%), illumination shifted unexpectedly from the small to the large or from the large to the small cylinder at the onset of the reach. For Condition One trials subjects were given no instructions as to which grasp to use. With perturbation, they thus naturally changed grasp from precision grip to whole hand prehension or vice versa. The results for the PD subjects indicated a slowness at the transition from one to another grasp. This contrasted to the smooth transitions when perturbation required only a change of grasp aperture (precision grip—Condition Two; whole hand prehension—Condition Three). PD subjects thus showed dysfunction in the suppression/activation of different grasp programs rather than deficits in the on-line modification of an operating program.

Key Words: Parkinson's disease; motor control; perturbation; reach; grasp.

INTRODUCTION

The aim of this study was kinematically to assess how Parkinson's disease (PD) subjects respond to a perturbation of the grasp component of a reach to grasp movement. The reason for using such an assessment is related to the reported dysfunction of this subject group in the switching from one to another motor pattern [4, 30, 46].

Although a common clinical observation, quantitative evaluation of this dysfunction has been sparse. In an early study, Talland and Schwab [46] found that when performing a sequence of movements (marking specified alphabetic letters) PD subjects had "difficulties in switching from one criterion to another" [46, p. 51]. Angel *et al.* [2] demonstrated that PD subjects took longer than controls to arrest a false computer joystick move prior to generating the correct move. They attributed this to a dysfunction in the ability to rapidly switch to a motor program for the opposite movement direction. Later research by Benecke *et al.* [4] was of the sequential performance of the "simple" but separate motor patterns of elbow flexion and isometric opposition between the index finger and thumb in one limb. For

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PD subjects, movement time of the sequential task was longer than that which would be expected by simply adding the individual movement times of each motor pattern task when performed in isolation. Such an increased movement duration could largely be attributed to a prolongation of the interval between termination of the first pattern and activation of the second. Harrington and Haaland [30], in a comparison of the sequential performance of one hand task to the sequential performance of distinct hand postures (e.g. from pressing a button with the tip of the index finger to grasping a handle), not only showed longer inter-response times for the PD subjects with the latter task but a greater incidence of error.

Another means of investigating this dysfunction with sequential movement has been with the kinematic assessment of the reach to grasp movement [5, 11, 15, 16]. Using this technique it has been shown that PD subjects show a comparatively long time between activation of the reach (transport) component and the later activation of the grasp (manipulation) component [15, 16]. In other words, the sequential activation of these components is barely perceptible (<50 msec) for non-PD subjects but for PD subjects the intercomponent period becomes more obvious, the mean being 90 msec [5, 11, 15, 16].

By perturbing the reach to grasp movement further information is given about how PD subjects are able to change motor output. In one such study, Castiello and Scarpa [15] perturbed the reach component by requiring subjects unexpectedly to reach to grasp an object at 27.5 or 40 cm instead of one at 15 cm. Apart from the greater movement durations, they found that PD subjects showed the same patterning in response to perturbation as that of control subjects. As an example, the first peak of arm acceleration for perturbed trials was earlier than the single peak of non-perturbed trials for both subject groups. This indicates the activation of prompt mechanisms to rearrange the motor output for successful end-task performance [14, 15, 41]. Of note, however, is that there was no evidence for a prolongation between closure of the first and opening of the second pattern. It can be suggested that this was because there was no requirement to open a new motor program; rather, an existing program (that of reaching in a particular direction) was modified on-line.

A perturbation that does, in contrast, prompt a change of motor program is that used by Castiello *et al.* [9, 10, 12, 13]. In this paradigm, the manipulation component is perturbed by unexpectedly changing the size of the object to be grasped. If no instruction is given as to the type of grasp to adopt, subjects naturally switch grasp type from, for example, precision grip [37] for a small object, to whole hand prehension, a grasp involving more digits, for a large object. Using this paradigm in a single case study of a hemiParkinson subject [9] a transition period between these two grasps was more evident on the clinically affected than on the unaffected side.

The results for the hemiParkinson subject pointed to the necessity for further investigation of a group of PD subjects with bilateral signs and symptoms. In the current study, the same grasp perturbation paradigm of the previous non-PD and hemiPD studies [9, 10, 12, 13] was thus employed, that is, PD and control subjects were required to respond to a perturbation of object size and were given no instructions as to which grasps should be used (Condition One). If PD subjects have difficulties in the switching from one to another program it was anticipated that dysfunction should be evident at the transition from one grasp type to the other. For example, with a perturbation from a small to a large object a delay between closure of the precision grip pattern and opening of the whole hand prehension pattern would be expected.

Two further conditions, referred to as "constrained" conditions were also included in this experiment. This was to enable a comparison between the results from a condition whereby

subjects changed from one motor program to another (Condition One) to those results obtained when subjects changed the characteristics of an existing program on-line (Conditions Two and Three). Under the constrained conditions subjects were instructed to use only one grasp type irrespective of target size [12, 40]. In Condition Two this was precision grip and subjects thus changed the grip aperture between index finger and thumb with perturbation of object size. In Condition Three only whole hand prehension was required. For PD subjects it was expected that the transition from one to another grasp aperture would show different results from the transition from one to another grasp type.

METHODS

Subjects

Details of the subjects which were assessed are shown in Table 1. The 15 Parkinson subjects had a diagnosis of idiopathic Parkinson's disease which was of 1–8 years standing. According to the Hoehn and Yahr scale [31], all were at stages 1 or 2. Signs and symptoms were bilateral in all cases, with one side usually being worse than the other. The level of rigidity and tremor was minimal at the time of testing. Three Parkinson subjects were *de novo*. Medication for the remaining subjects was most commonly Sinemet or Eldepryl. Parkinson subjects were always tested during a period of least signs and symptoms, 1–2 hr after medication, and none showed motor complications due to medication. The 15 age and sex matched controls (52–71 years; female $n=5$; male $n=10$) reported no neurological or skeletomotor dysfunctions. All PD and control subjects showed right handed dominance with an average score of 18 on the Edinburgh inventory [38]. All were naive as to the experimental design.

Table 1. Details of the Parkinson and control subjects

Subject number	Control subjects		Parkinson subjects				
	Sex	Age	Sex	Age	Hoehn and Yahr scale	Diagnosis (years)	Medication
1	F	62	F	63	2	2	Sinemet/Deprenyl
2	F	61	F	60	1	8	Sinemet
3	M	64	M	66	2	1	Sinemet
4	F	67	F	67	2	7	Sinemet/Eldepryl
5	M	65	M	65	2	6	Sinemet
6	M	70	M	69	2	5	Sinemet
7	M	68	M	71	1	5	Eldepryl
8	M	69	M	72	2	3	Sinemet
9	F	52	F	52	1	2	Sinemet/Deprenyl
10	M	57	M	57	2	1	Nil
11	M	61	M	62	1	1	Nil
12	M	59	M	61	1	4	Sinemet
13	M	71	M	68	1	6	Sinemet
14	F	59	F	58	2	1	Nil
15	M	60	M	60	1	5	Sinemet/Eldepryl

Apparatus

The working surface was that of a rectangular table. The subject was seated on a height adjustable chair so that the thorax pressed gently against the front edge of the table and the feet were supported. A pressure sensitive starting switch was positioned 10 cm anterior to the subject's midline. With the ulnar side of the hand placed upon this switch, the starting position was slight shoulder flexion, 90° of elbow flexion, semipronation of the forearm, 5–10° wrist extension and opposition between the pads of the index finger and thumb.

Reflective passive markers (0.5 cm diameter) were secured to the following points of the reaching limb: (a) Wrist—radial aspect of the distal styloid process of the radius; (b) dorsal aspect of the first carpo-metacarpal joint; (c) thumb—ulnar side of the nail; and (d, e, f) index, middle and ring fingers—radial side of the nail. Movements were recorded with the Elite system [25]. This consisted of two infra-red cameras (sampling rate 100 Hz) inclined at an angle of 30° to the vertical and placed 3 m in front of the table and 3 m apart. The calibrated working space was a

parallelepiped (length 60 cm, breadth 30 cm, height 60 cm) from which the spatial error measured from stationary and moving stimuli was 0.4 mm. Calibration was performed using a grid of 25 markers (5 × 5). The centroid of each marker was placed 15 cm from that of another. Using the procedure of Haggard and Wing [29] the mean length of a bar with two markers attached, as reconstructed from the Elite data, was 14.93 (S.D. 0.22 cm). Coordinates of the markers were reconstructed with an accuracy of 1/3000 over the field of view and sent to a host computer (IBM 386). The S.D. of the reconstruction error was 1/3000 for the vertical (Y) axis and 1.4/3000 for the two horizontal (X and Z) axes.

The target stimuli to be grasped were two translucent perspex cylinders. A small cylinder (diameter 0.7 cm, height 10 cm, weight 9 g) stood vertically within the centre of a large cylinder (diameter 7.5 cm, height 8 cm, weight 202 g). The small cylinder was thus slightly higher than the large cylinder. These cylinders were positioned over three computer controlled light emitting diodes (LEDs) implanted in the table surface 35 cm anterior to the starting switch in the midline. With activation of the central LED only the small cylinder was illuminated. With activation of the two lateral LEDs, only the large cylinder was illuminated. Perturbation of object size was achieved by a shift of illumination [9, 10, 12, 13, 40]. This was triggered immediately upon release of the starting switch, that is, at the onset of the reaching (transport) movement. For a perturbation from large to small cylinder, the initially activated lateral LEDs were deactivated and the central LED was activated. The subject thus initially saw the large cylinder illuminated but, upon initiation of the reach movement, saw a shift of illumination to the small cylinder and was required to grasp this latter target. For a perturbation from small to large cylinder, the initially activated central LED was deactivated and the two lateral LEDs were activated. The subject thus initially saw the small cylinder but, upon movement initiation, saw a shift of illumination to the large cylinder and was required to grasp the latter target.

Procedure

The subject was instructed to begin the movement as soon as a cylinder became illuminated, and then reach for, grasp and lift the cylinder. No instructions were given as to speed of initiation, speed of movement or accuracy. For 10 practice trials, all subjects naturally adopted a precision grip (opposition between the index finger and thumb [37]) to grasp the small cylinder and whole hand prehension (all fingers opposing the thumb) to grasp the large cylinder. Prior to each trial a tone (880 Hz; duration 250 msec) was generated. To reduce expectancy and rhythmical effects, the duration between this tone and illumination was randomly set at 500, 1000, 1500 or 2000 msec. During each trial, the experimenter ascertained continued on-line detection of the markers and if any markers were not visible the trial was rejected. Computer control of a further trial was then initiated and 2 sec later a tone for this new trial sounded. Data acquisition began with illumination of the cylinder and continued until after the cylinder had been lifted. Experimentation continued until the required number of successful trials was collected.

Trials were performed under one of three conditions. Condition One (Unconstrained Prehension) was of primary focus for the purposes of this experiment. In this condition the subjects were given no instruction as to what type of grasp to use, and all naturally adopted a precision grip for the small and a whole hand prehension for the large target. In Condition Two (Precision Grip) subjects were instructed to use a precision grip for both the small and the large target while in Condition Three they were instructed to use a whole hand prehension irrespective of object size. To prevent the constrained grasps influencing the patterning of the unconstrained grasps, Condition One was always performed first. The presentation order of Conditions Two and Three was then counterbalanced across subjects. In order to prevent fatigue and lack of attention/concentration each of the three conditions was tested on a separate day over a one week period. Testing was always at the same time of day in relation to medication. Marker position was kept constant across experimental sessions by marking the points of application with indelible ink.

For each condition, 100 trials were tested. The majority of these were non-perturbed trials whereby either the small ($n=40$) or the large ($n=40$) cylinder was illuminated and this same cylinder remained illuminated until after completion of the trial. For 20% of the trials a visual perturbation occurred immediately upon movement onset (see previously). These perturbed trials were random and interspersed with the non-perturbed trials. The perturbation consisted of a shift of illumination either from large to small cylinder ($n=10$) or from small to large cylinder ($n=10$). For Condition One, these perturbations thus promoted the shift from one distal pattern to another, that is, from whole hand prehension to precision grip or vice versa. In contrast, for Conditions Two and Three the requirement was for a change of grip aperture, either from large to small or vice versa.

Data processing and analysis

The Elite processing package was used to assess the data. This gave a three-dimensional reconstruction of the marker positions. The data were then filtered using a FIR linear filter and a transition band of 1 Hz (sharpening factor = 2 [22]). Analysis of the transport component was based on kinematics of the wrist marker: trajectory, velocity and acceleration. Onset of this component was taken as the time shortly after illumination and release of the starting switch at which the wrist marker exceeded a displacement of 0.4 mm; movement completion as the time of object grasp at which the distance between the thumb and index finger markers was constant, indicating that the cylinder had been grasped. The lifting feature of the task was not assessed. Movement duration refers to the time between onset and completion. Temporal measures included the times taken to reach peak velocity, peak acceleration and peak deceleration and the time from peak velocity to the end of the transport component

(deceleration time); each value was expressed in both absolute and relative (i.e. as a percentage of movement time) terms. The amplitudes of peak velocity, peak acceleration and peak deceleration were also determined.

Analysis of the manipulation component was based on the kinematics of the hand and digit markers: trajectory of each digit, grip aperture and the rate of change of the grip aperture. Temporal measures, again expressed in both absolute and relative terms, included the time to peak aperture and, in cases of a second aperture (see Results), the onset time of this second opening (calculated with a break detection algorithm [12]) and the time of its peak. Middle and ring finger trajectories were also analyzed. The time at which the index finger deviated from the more ulnar digits for specification of precision grip could thus be determined [12]. Amplitude measures included the amplitude of the first, and where present, second peak of aperture between the index finger and thumb.

The mean value (absolute and relative) of each measure for each subject was entered into an analysis of variance (ANOVA; 0.05 alpha level of significance). Mean and S.D. values of the pooled subject results, with emphasis upon Condition One trials, are indicated throughout the text and tables. S.D. values are high due to inter-subject variability—for each subject, however, the S.D. of all parameters was consistently below 10% of the mean. *Post-hoc* contrasts were conducted with the Newman–Keuls testing procedure. For each group, perturbed trials from large to small were compared to non-perturbed trials to the large cylinder. Perturbed trials from small to large cylinder were compared to non-perturbed trials to the small cylinder. Each pair of perturbed and non-perturbed trials was also compared across condition. Regression analysis was used to assess correlations between specific temporal parameters of each component. The Fisher-Z transformation of data was used for homogeneity of variance and to counteract any non-normal distributions, and the significance of each correlation was assessed with the Student *t*-test.

RESULTS

For PD subjects, the results indicated a dysfunction at the transition phase from one grasp to another in the perturbed trials of Condition One.

Looking first at the perturbation from small to large object, the PD subjects showed a clear slowness between closure of the precision grip pattern and opening of the whole hand prehension pattern. This is illustrated in Fig. 1(A) where a plateau between the first point of inflection, most probably indicative of peak aperture for the small cylinder, and the onset of the second opening for the large cylinder is evident. Such a plateau was present for 73% of the Condition One perturbed trials of PD subjects. The mean duration of this plateau was 398 msec, that is, 28% of the total movement duration. For the perturbed Condition One trials of the control subjects there were no examples of a plateau (e.g. see Fig. 1(A)). Instead, the grip aperture profile showed either an inflection with an average duration of 106 msec (9%) or a very smooth and almost undetectable transition between the two grasps.

A plateau was also not present for the PD subjects' perturbed trials of Conditions Two and Three, that is, when only a change of aperture was required. As shown in Fig. 1(B) and (C), there was either an inflection at the change from one to another aperture or a very smooth transition. In those cases where an inflection was more evident, a break detection algorithm [12] was used to determine its onset and the subsequent onset of the second hand opening. With an estimated error of 10–20 msec using this algorithm, the average duration of the inflection was 71 msec (5%) for Condition Two perturbed trials and 54 msec (4%) for Condition Three perturbed trials of the PD subjects (Table 2). Clearly the transition from a small to a large grasp aperture for this subject group was faster and smoother than the transition from precision grip to whole hand prehension. This smooth transition was also comparable to those observed for the control subjects where the average inflection duration for Condition Two perturbed trials was 60 msec (5%) and for Condition Three trials was 49 msec (4%).

Table 2 shows the values of manipulation component parameters measured from the grip aperture profile. A comparison of the transition duration between the Condition One grasps to that between the small and large apertures of Conditions Two and Three demonstrates that PD subjects were much slower in closing one grasp and then opening another than in changing grip aperture. The control subjects also showed a longer transition between grasps

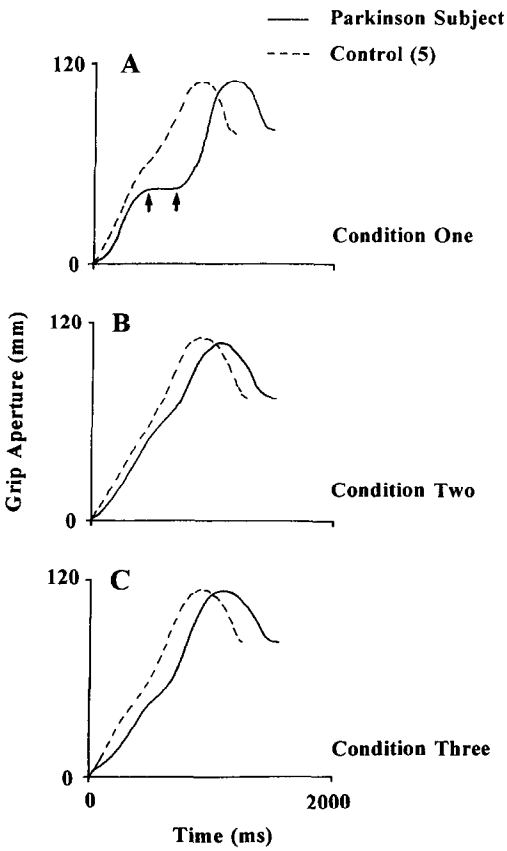

Fig. 1. Grip aperture profiles from single perturbed trials from small to large cylinder for Parkinson subject 5 and Control subject 5. (A) Condition One—note plateau of grip aperture for the PD subjects in changing from precision grip to whole hand prehension. The filled arrows indicate the onset and end times of this plateau. (B) Condition Two. (C) Condition Three.

than between aperture sizes. However, in absolute and particularly in relative terms the Condition One transition period of this subject group was much shorter than that of PD subjects (9 and 28%, respectively). Table 2 also illustrates that peak grip aperture was later for the Condition One perturbed trials of the PD subjects (939 msec; 66%) than for the Condition Two and Three trials [875 msec, 60%; 829 msec, 61%; Interaction Group by Condition $F(2, 56)=24.14$, $P<0.0001$]. However, of great interest was that despite the transition plateau and this later peak grip aperture the movement duration of the Condition One trials was no longer than that for the Condition Two and Three trials. In other words, the obvious and lengthy reparameterization of the manipulation component did not result in a longer reaching time.

With the opposite perturbation from large to small object, there was again evidence of a dysfunction at the transition between the two grasp types. This was shown by the time at which the index finger "specified" for precision grip, that is, when this finger began to show a flexion/opposition movement independent of the other fingers. For PD subjects this specification was 10% of movement duration later than for control subjects ($P<0.01$). In

Table 2. Perturbed trials: Small to large cylinder. Comparison across conditions for manipulation component parameters and movement duration

	Onset of inflection (msec, %)	End of inflection (msec, %)	Time of peak grip aperture (msec, %)	Movement duration (msec)
Parkinson's disease subjects				
Condition One	371 (85)	769 (171)	939 (270)	1420 (350)
	26 (6)	54 (12)	66 (19)	
	398 msec (28%)			
Condition Two	359 (102)	430 (122)	875 (300)	1455 (356)
	25 (7)	30 (8)	60 (21)	
	71 msec (5%)			
Condition Three	373 (96)	427 (130)	829 (180)	1370 (357)
	27 (7)	31 (9)	61 (13)	
	54 msec (4%)			
Control subjects				
Condition One	284 (57)	390 (101)	721 (183)	1147 (209)
	25 (5)	34 (9)	63 (16)	
	106 msec (9%)			
Condition Two	267 (59)	327 (96)	678 (107)	1186 (247)
	23 (5)	28 (8)	57 (9)	
	60 msec (5%)			
Condition Three	269 (68)	318 (82)	725 (221)	1139 (315)
	24 (6)	28 (7)	64 (19)	
	49 msec (4%)			

Inter-subject mean and standard deviation (parentheses) values are indicated for each parameter. The relative value of each parameter (%) is shown below the absolute value (msec). Onset of inflection, End of Inflection and Peak Grip Aperture are measured from the grip aperture profile. Duration of the inflection is indicated below each pair of inflection values.

other words, the opening of the precision grip pattern was delayed in this subject group. This pointed to a prolongation of the transition between closing whole hand prehension and opening precision grip.

Despite a dysfunction at the transition phase, in all other respects PD subjects showed the same response pattern to perturbation as control subjects. This was firstly evident by simply observing the perturbed movements. Like control subjects, PD subjects could respond to the visual size perturbation and could generate changes to the initially outputted motor pattern. Not unexpectedly, they were slower. Yet, like controls, they showed no statistical increase of movement duration when comparing the perturbed to the non-perturbed Condition One trials (see Tables 3 and 4).

By perturbing object size the perturbation obviously affects patterning of the manipulation component. A parameter of interest in this component is the time at which the hand reaches maximum aperture. PD subjects showed a very similar patterning of this parameter in response to perturbation as control subjects. Table 3 gives the intersubject means for the perturbed large to small and non-perturbed large trials of Condition One. It can be seen that maximum grip aperture was earlier for perturbed than for non-perturbed trials [Interaction Condition by Trial $F(2, 56) = 43.28$, $P < 0.0001$; Fig. 2]. That is, the initially activated whole hand prehension was curtailed so that precision grip could be mobilized. Peak grip aperture for the perturbed trials of PD subjects was at an average of 809 msec but at 1008 msec for non-perturbed trials. The same pattern of anticipation with perturbation was observed for control subjects—561 vs 653 msec, respectively. With the opposite perturbation this

Table 3. Perturbed trials: large to small cylinder; non-perturbed trials: large cylinder

	Parkinson subjects		Control subjects	
	Perturbed	Non-perturbed	Perturbed	Non-perturbed
Movement duration (msec)	1333 (322)	1356 (357)	1047 (142)	1009 (170)
Transport component				
Time to peak deceleration (msec)	841 (194)	893 (211)	603 (84)	621 (107)
(%)	58 (6)	66 (8)	58 (5)	63 (7)
Amplitude peak deceleration (mm/sec^2)	1578 (446)	1386 (496)	2633 (883)	2590 (645)
Deceleration time (msec)	824 (276)	752 (250)	654 (109)	588 (130)
(%)	57 (6)	55 (5)	62 (4)	58 (6)
Manipulation component				
Time to specification for precision grip (msec)	743 (76)		481 (103)	
(%)	53 (8)		46 (9)	
Time to maximum grip aperture (msec)	809 (219)	1008 (308)	561 (107)	653 (146)
(%)	57 (6)	74 (4)	53 (7)	65 (9)
Amplitude of maximum grip aperture (mm)	86 (20)	116 (8)	78 (15)	127 (7)

Inter-subject mean and standard deviation (parentheses) values are indicated for each parameter. For temporal parameters the relative value of movement duration is shown below the absolute value.

Table 4. Perturbed trials: small to large cylinder; non-perturbed trials: small cylinder

	Parkinson subjects		Control subjects	
	Perturbed	Non-perturbed	Perturbed	Non-perturbed
Movement duration (msec)	1420 (350)	1424 (363)	1147 (209)	1099 (247)
Transport component				
Time to peak deceleration (msec)	884 (186)	926 (196)	596 (134)	646 (149)
(%)	63 (7)	66 (4)	52 (4)	59 (6)
Amplitude peak deceleration (mm/sec^2)	1625 (582)	1340 (489)	2635 (900)	2410 (740)
Deceleration time (msec)	825 (347)	812 (284)	761 (197)	700 (147)
(%)	57 (9)	56 (5)	68 (4)	64 (4)
Manipulation component				
Time to specification for precision grip (msec)	321 (97)	513 (148)	230 (45)	236 (50)
(%)	24 (8)	37 (8)	20 (3)	20 (5)
Time to maximum grip aperture (msec)	939 (270)	890 (228)	721 (183)	677 (116)
(%)	66 (19)	63 (5)	63 (16)	62 (8)
Amplitude of maximum grip aperture (mm)	101 (17)	56 (11)	122 (15)	62 (13)

Inter-subject mean and standard deviation (parentheses) values are indicated for each parameter. For temporal parameters the relative value of movement duration is shown below the absolute value.

parameter was later for perturbed than for non-perturbed trials, and, again, both groups showed this pattern (Interaction Condition by Trial $F(2, 56) = 3.87$, $P < 0.05$; see Table 4). Further, results for the two groups were also similar under Conditions Two and Three, and mirrored those found in a previous non-PD study [12]. The timing of peak grip aperture showed no difference when comparing perturbed to non-perturbed trials. As a brief example, peak grip aperture of the Condition Two perturbed small to large trials of PD subjects was at an average of 875 msec (60%) while for the non-perturbed trials it was at 873 msec (62%). For control subjects the perturbed and non-perturbed values were 678 msec (57%) and 681 msec (62%), respectively.

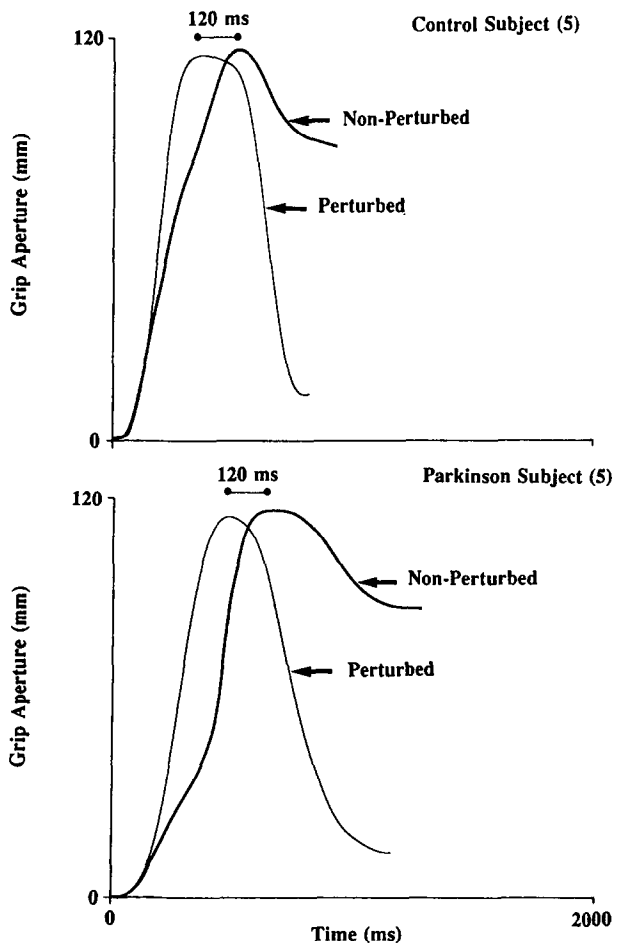

Fig. 2. Grip aperture profiles for a single *Perturbed* trial from large to small cylinder and a *non-perturbed* trial to the large cylinder (Condition 1). Above: control subject 5. Below: Parkinson subject 5. *120 msec* refers to the earlier timing of the peak grip aperture for perturbed than for non-perturbed trials.

The amplitude of maximum grip aperture also showed a similar patterning across the two groups. With the perturbation from large to small cylinder (Condition One) this maximum aperture was less than that for non-perturbed large trials (Table 3). This if further evidence that both groups closed the whole hand prehension pattern at an earlier stage in order to execute precision grip. For the opposite perturbation the maximum grip aperture was suitable for the end-task of grasping the large cylinder. PD subjects again showed a similar patterning of this parameter as that of control subjects (see Table 4).

Previous studies with non-PD subjects have shown that perturbation of primarily the grasp component also affects the kinematic patterning of the transport component [10, 12]. In the current study, the same result held for PD subjects, and the changes with perturbation for this group were similar to those for control subjects.

Peak arm deceleration was earlier for the perturbed than for the non-perturbed trials of Condition One (Interaction Condition by Trial: perturbed small to large vs non-perturbed small—$[F(2, 56] = 18.78$, $P < 0.0001]$; perturbed large to small vs non-perturbed large—$[F(2, 56) = 7.34$, $P < 0.01]$; Fig. 3). This is shown in Tables 3 and 4. For example, with the perturbation from small to large cylinder, this peak for the PD subjects was at an average of 884 msec but at 926 msec for non-perturbed trials. The amplitude of peak deceleration also showed the same response to perturbation for both groups, that is, it was greater for perturbed than for non-perturbed trials (Interaction Condition by Trial: perturbed small to large vs non-perturbed small—$F(2, 56) = 15.92$, $P < 0.0001$; perturbed large to small vs non-perturbed large—$F(2, 56) = 4.48$, $P < 0.05$). The parameterization of arm deceleration was thus affected by the perturbation requirement of having to change grasp type. In contrast, and again for both groups, neither the timing nor the amplitude of peak deceleration showed changes with perturbation under Conditions Two and Three (see also results for non-PD subjects in Ref. [12]).

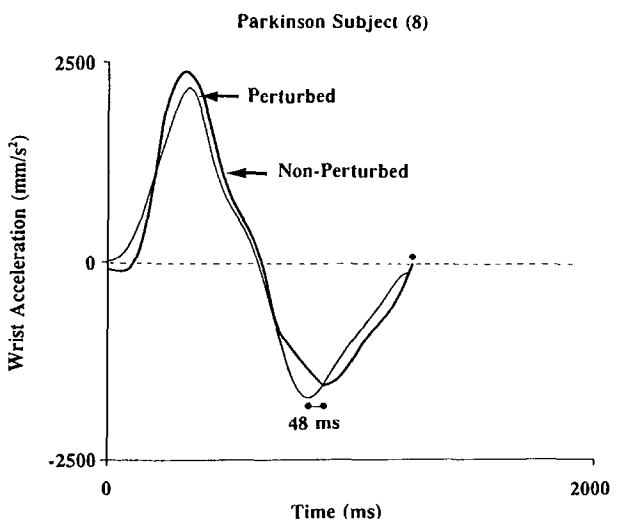

Fig. 3. Wrist acceleration profiles for *Perturbed* trials from small to large cylinder and *Non-perturbed* trials to the small cylinder (Parkinson subject 8). Condition 1 trials. *48 msec* indicates that peak deceleration was earlier for perturbed than for non-perturbed trials.

The time allocated to deceleration of the arm towards the final target also showed similar effects of perturbation across the two subject groups. This time, from peak velocity until the end of the movement, was longer for perturbed than for control trials (perturbed small to large vs non-perturbed small—[$F(1, 28) = 3.3$, $P < 0.05$]; perturbed large to small vs non-perturbed large—[$F(1, 28) = 80.33$, $P < 0.0001$]). For example, and as shown in Table 3, the deceleration time of PD subjects for the perturbed large to small trials showed a mean of 824 msec while for non-perturbed large trials the mean was 752 msec. The same augmentation of deceleration time with perturbation was found for control subjects and with the opposite perturbation from small to large cylinder (see Table 4). Similarly, deceleration time was generally longer for the perturbed Condition Two and Three trials than for the non-perturbed trials of both subject groups. However, the means of achieving this longer approach time was with a prolongation to movement duration rather than an anticipation of transport kinematic parameters. For example, with perturbed Condition Two trials from small to large cylinder, PD subjects showed an average movement duration of 1455 msec as opposed to 1397 msec. Control subjects showed a duration of 1186 msec as compared to 1096 msec, respectively [Interaction Condition by Trial $F(2, 56) = 5.56$, $P < 0.01$]. The same increase of movement duration with perturbation was found for the opposite perturbation [Interaction Condition by Trial $F(2, 56) = 9.21$, $P < 0.0001$].

A further indication that the patterning of the perturbed trials was similar for PD and for control subjects was given by the results from the regression analyses performed between parameters measured from the transport and manipulation components. Perturbation did not, for example, disrupt temporal coupling between peak deceleration and peak grip aperture. For perturbed large to small trials of Condition One, the correlation coefficients obtained from the regression analysis between these two parameters were $r = 0.81$ ($P < 0.0001$) and $r = 0.84$ ($P < 0.0001$) for the Parkinson and controls subjects, respectively. For the opposite perturbation, the coefficients were $r = 0.78$, $P < 0.0001$ and $r = 0.60$, $P < 0.05$, respectively. Under Conditions Two and Three, correlations between these two parameters were also evident during perturbed trials.

DISCUSSION

Parkinson subjects suitably adapt movement parameterization when unexpectedly confronted with a perturbation of object size. This concurs with previous results which indicate that Parkinson subjects are able to adequately respond to unexpected perturbations [27, 34]. Essentially the patterning to achieve these rapid modifications is similar to that of control subjects. Thus, for perturbed Condition One trials whereby the switch is either from precision grip to whole hand prehension or from whole hand prehension to precision grip, movement duration is no different from that of non-perturbed trials. This equivalence is despite obvious transition phases during execution and is primarily achieved by the rescaling of one parameter of the transport component. Peak deceleration of the arm, a reflection of braking as the hand approaches the object, is earlier and greater for perturbed trials. This finding also applied to the control subjects and reproduces results from studies of younger non-Parkinsonian subjects [10, 12]. Changes to the manipulation component are thus 'recognized' by the neural channels for transport and the rapid adaptations which follow are appropriate to allow an adequate approach phase for the newly presented stimulus.

As predicted by Marsden [32, 33], PD subjects, in summary, show no deficit in the ability to pattern movements. This has also been found with previous kinematic studies of the reach

to grasp movement with this subject group. For example, PD subjects suitably adjust kinematic parameterization according to the size and to the location of the object to be grasped [11, 15, 16]. Though activation of a movement is disturbed (see following), once initiated, the movement demonstrates appropriate patterning and coordination. This suggests that the basal ganglia do not determine the basic structuring or modelling of well-rehearsed and functional motor components such as those required in a reach to grasp movement.

It is established that Parkinson subjects have a dysfunction with the simultaneous or sequential activation of motor programs [3, 4, 30, 44, 46]. The current study gives a kinematic qualification to the description of this dysfunction showing it to be evident at transition phases whereby the suppression of one and the activation of another motor program is required. For perturbed Condition One trials, slowness in movement suppression/activation is found when Parkinson subjects are required to change from one type of grasp to another. For perturbation from whole hand prehension to precision grip a prolonged transition is indicated by the relatively later specification of precision grip. For the perturbation from precision grip to whole hand prehension a plateau of grip aperture, lasting for around 28% of movement duration, is evident prior to activation of whole hand prehension.

The control channels for precision grip are thought to differ from those for whole hand prehension [35, 36, 42]. For Parkinson subjects, Benecke *et al.* [3, 4] described particular deficits with the activation of separate motor programs, that is, those which showed no evidence of being controlled by a single complex motor program [cf. 8]. As evidenced by the long transition from precision grip to whole hand prehension, the results of the current study are in agreement with these findings. Abnormality is clearly evident when suppression/activation is of motor patterns which are subserved by different neural substrates.

Two main but distinct arguments could be advanced to explain these delays. One is that the Parkinson subject places greater emphasis upon the utilization of movement related feedback. The second is that these subjects have a central delay in the activation and probably also in the suppression of motor programs.

Previous studies have demonstrated that Parkinson subjects become more dependent upon visual feedback to guide movement [20, 26, 45]. As proposed by Goldberg [28], this could reflect greater reliance upon the responsive, feedback dependent, lateral, premotor system involving the arcuate premotor area and the cerebellum. The current study has not manipulated feedback and cannot make any definitive conclusions as to the degree to which it is used by Parkinson subjects. The prolonged transition between closure of one grasp and opening of another could, however, represent processing times of visual and proprioceptive information from the hand. On-line movement feedback could then be utilized for the change from one grasp to the other. Thus, for the perturbed trials from precision grip to whole hand prehension the transition took about 400 msec. This is more than sufficient time to allow for the processing of feedback and activation of whole hand prehension.

It has been suggested that a greater utilization of feedback may avoid the errors associated with the non-feedback movement performance by Parkinson subjects [21, 23]. The current study did not specifically address the incidence of errors in the performance of the reach to grasp movement. Nevertheless, it was clear that Parkinson subjects adapted quickly to the perturbation and successfully performed the end-task. Further, despite transition periods from one grasp to another, coordination between arm transport and hand opening was maintained. For perturbed trials, Parkinson subjects continued to show temporal

coordination between the point of maximum arm deceleration and that of maximum grip aperture. Feedback during the transition period could thus assist in ascertaining the current status of each component for activation of the second grasp pattern and for intercomponent recalibration.

Together with the supplementary motor area, the basal ganglia are thought to form a medial system which operates largely in a feed-forward mode (see [28] for review). The explanation that the delays of movement activation are reflective of a greater dependence upon feedback processing implies that this medial system has been bypassed and that Parkinson subjects turn "to remaining functions of the relatively spared lateral premotor system to attempt to substitute for those lost through medial system impairment" ([28], p. 582). An alternative argument is that the medial system **has** been activated. The delays of movement suppression/activation would then directly reflect dysfunction of the basal ganglia rather than rerouting strategies.

The motor circuit (medial system) is thought to consist of multiple cortico-striato-nigro-thalamocortical circuits arranged in a parallel and topographical manner [1, 39]. With the loss of striatal influence resulting from dopamine depletion, an increased inhibition of the thalamocortical pathway has been proposed [19, 24]. Areas within the supplementary motor area and motor cortex would thus be less responsive to activation—the pattern of "readiness" to triggers from sources other than that of the basal ganglia, having not been set. If this lack of responsiveness were confined to a specific neural channel (e.g. whole hand prehension or precision grip) this would explain why a movement shows a delay of activation.

The results suggest that the dysfunction is of both suppression and of activation. Looking, for example, at the change from precision grip to whole hand prehension, the task here is not only to activate channels for whole hand prehension but to suppress channels for precision grip. Evidence that there may be some difficulty in "releasing" the first pattern is given by the prolonged grip aperture plateau. It is as if the expression of the goal of the initially prescribed pattern perseverates. This observation may justify a qualification to the role of the basal ganglia. Not only could these nuclei set cortical excitability for an upcoming movement but they could also assist in the cancelling of already activated channels. Brotchie *et al.* [6, 7] found a proportion of neurones in the anterior globus pallidus which showed phasic discharge in relation to the end of a wrist movement. It was proposed that this mechanism could operate both to terminate sustained activity in the supplementary motor area for an existing movement and to prepare for execution of the forthcoming movement. In Parkinson subjects the absence or dysfunctioning of this phasic influence could lead to a long transition between closure of precision grip channels and activation of those for whole hand prehension.

There is a clear difference of results when comparing the change from one to another motor pattern (such as precision grip to whole hand prehension) to the change of amplification of an existing distal pattern (such as from a small to a large precision grip). In those experimental conditions whereby the same grasp is maintained throughout the trial, Parkinson subjects show a smooth transition from small to large aperture. A number of statements can be made from this result. Firstly, this result adds further support to the contention that the basal ganglia are not directly involved in the execution of a movement pattern once it is in operation. This concurs with the electrophysiological findings of Brotchie *et al.* [6] who found that pallidal neurons show little relationship to movement parameters such as the amplitude of angular wrist movement or the amount of torque production. Secondly, the

rapidity of the change of aperture in the current experiment indicates that the long transition from precision grip to whole hand prehension cannot be attributed to mechanical factors. For example, rigidity does not limit the speed with which the fingers can open for a larger grip. Finally, the results cannot be confidently explained by problems in the shifting of attentional focus which have been reported for Parkinson subjects (e.g. [43]). For example, the prolonged transition from precision grip to whole hand prehension could result from a slowness in enlarging the focus of attention from the small to the large cylinder [17, 18]. The later activation of the second pattern could thus reflect a period of waiting until the focus has sufficiently prepared for the action [47] but such a long transition would also be expected for those conditions requiring a change of aperture from small to large. This was not the case. However, the qualitative nature of the movement shift in changing from precision grip to whole hand prehension is likely to be much greater than that in changing from a small to a large aperture. Thus, the attentional requirements of the former condition could be greater than those of the second and thus more vulnerable to set shifting impairment.

Several issues are raised by this work. For a well-rehearsed task, such as reaching to grasp, Parkinson subjects show appropriate kinematic patterning and coordination (see also [11, 15, 16]). When a visual size perturbation is applied to this movement, they show rapid and suitable adjustments. Neural execution pathways, which include the motor program or movement model, thus do not appear to be affected by Parkinson's disease. It is important to note, however, that factors such as the experimental paradigm, stage of the disease process and medication need further investigation before drawing definitive conclusions as to this "normality". A second issue relates to the interpretation of these results at the neural level. Do the delays of movement activation represent a dysfunction because the basal ganglia and medial system are employed or are they the manifestation of a compensation strategy whereby there is rerouting to alternative neural channels? This question would be best addressed by manipulation of feed-forward and feedback mechanisms and with neurophysiological studies.

Acknowledgements—The Parkinson and control subjects who participated in this study are warmly thanked. In addition we extend our gratitude to Prof. Steven Keele and Dr Marina Scarpa. Prof. Razzaboni is thanked for allowing us to use the excellent facilities at the European Medical Centre and Mrs Uguzzoni is gratefully acknowledged for her generous assistance with the subjects.

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