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RESEARCH ARTICLES

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Deficits in adaptive upper limb control in response to trunk perturbations in Parkinson's disease

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Abstract The ability of patients with Parkinson's disease (PD) to compensate for unexpected perturbations remains relatively unexplored. To address this issue PD subjects were required to compensate at the arm for an unexpected mechanical perturbation of the trunk while performing a trunk-assisted reach. Twelve healthy and nine PD subjects (off medication) performed trunk-assisted reaching movements without vision or knowledge of results to a remembered target in the ipsilateral (T1) or contralateral (T2) workspace. On 60% of the trials trunk motion was unrestrained (free condition). On the remaining 40% of randomly selected trials trunk motion was arrested at movement onset (blocked condition). If subjects appropriately changed arm joint angles to compensate for the trunk arrest, there should be spatial and temporal invariance in the hand trajectories and in the endpoint errors across conditions. The control group successfully changed their arm configuration in a context-dependent manner which resulted in invariant hand trajectory profiles across the free and blocked conditions. More so, they initiated these changes rapidly after the trunk perturbation (group mean 70 ms). Some PD subjects were unable to maintain invariant hand paths and movement errors across conditions. Their hand velocity profiles were also more variable relative to those of the healthy subjects in the blocked-trunk trials but not in the free-trunk trials. Furthermore, the latency of compensatory changes in arm joint angles in movements toward T1 was longer in the PD group (group mean 153 ms). Finally, PD subjects' arm and trunk were desynchronized at movement onset, confirming our previous findings and consistent with PD patients' known problems in the sequential or parallel generation of different movement components. The findings that individual PD subjects were unsuccessful or delayed in producing context-dependent responses at the arm to unexpected perturbations of the trunk suggests that the basal ganglia are important nodes in the organization of adaptive behavior.

Keywords Basal ganglia · Reaching · Motor control · Perturbation

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Introduction

The flexibility (redundancy) of the sensorimotor system allows healthy individuals to adapt movement to changes in the environment. This ability often requires the rapid integration of afferent information with efferent signals to modulate an ongoing movement. Compensatory responses in intersegmental coordination have been reported to occur at latencies 20–50 ms after jaw perturbations during speech (Gracco and Abbs 1985) and at latencies less than or equal to 50 ms after trunk perturbations during arm reaching (Adamovich et al. 2001a; Tunik et al. 2003). Although the rapidity of such responses suggests that they

are mediated at lower levels in the neuraxis, it is not understood whether and how dysfunction of hierarchically higher centers (e.g., basal ganglia) influence the generation of such compensatory responses.

The role of the basal ganglia in adaptive control has been studied using visual perturbations by unexpectedly shifting the location of a target or its size during a reach-to-grasp movement (Inzelberg et al. 1996; Scarpa and Castiello 1994). Vision improves some aspects of movement in PD (Scarpa and Castiello 1994). Given the known deficits in higher level processing of proprioception and its integration with central commands (Adamovich et al. 2001b; Escola et al. 2002; Klockgether et al. 1995; Seiss et al. 2003), perturbations of the motor system may be an additional vehicle for understanding the role of the basal ganglia in adaptive control.

To address this issue we tested the ability of subjects with PD to compensate for the influence of an unexpected perturbation of the trunk on the hand position during trunk-assisted arm reaches to remembered target locations. Reaching movements involving the trunk may additionally be useful in determining general motor control deficits related to PD, irrespective of compensatory abilities. Preliminary results of this study have been presented in abstract form (Tunik et al. 2002).

Methods

Subjects

Nine patients with clinically diagnosed idiopathic Parkinson's disease and 12 healthy subjects participated in the study after signing consent forms approved by Rutgers University and the Rehabilitation Institute of Montreal. The mean age of controls (67.3 ±6.9 years) and that of PD subjects (67.8±11.6 years) subjects did not differ significantly. All subjects were right-hand dominant (Oldfield 1971). Patients were L-dopa responsive and in stage II or III as assessed on the motor section of the Unified Parkinson's Disease Rating Scale (UPDRS; Fahn and Elton 1987; Table 1). Subjects with any additional symptoms (e.g., Parkinson's plus), depression or dementia (assessed by Beck's Depression Inventory and Mini-Mental Examination), or more than mild tremor or dyskinesia were excluded from participation. All PD patients were tested in the morning before taking their medication, at least 12 h after their dose of the previous night. Table 1 shows that the PD subjects had only mild postural reflex deficits as measured by the UPDRS Pull Test (mean 1.1, range 0–2). This very mild postural reflex deficit occurred while the subjects were standing; when seated, as in the present study, balance demands are greatly diminished. Thus it is unlikely that the trunk motion of seated subjects would induce balance problems in the present experiment (see also "Results").

Apparatus and procedures

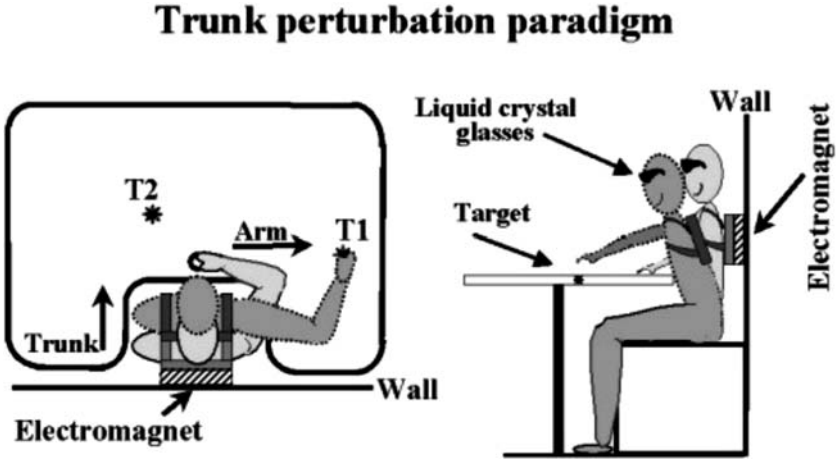
Figure 1A shows the experimental set up (see also: Adamovich et al. 2001a; Tunik et al. 2003). Light-emitting diodes embedded in a plexiglas table marked the target locations. The initial position was in the subjects' midsagittal plane about 30 cm from the sternum. One target (T1) was placed in the workspace of the dominant arm about 30 cm from the initial position, and oriented about 80° relative to the sagittal axis. Another target (T2) was placed in the contralateral workspace (about 15 cm and 45°, respectively). A trial began with the illumination of a target, cueing subjects to lift their entire arm several centimeters above the table. One second later liquid crystal glasses (Translucent Technologies) worn by the subjects became opaque, blocking their vision and an auditory signal cued the subject to initiate movement.

Subjects were required to perform a trunk-assisted arm reach to the remembered target location. Subjects were instructed to move quickly without touching the table, stop momentarily, and return their hand and trunk in a self-paced way to the starting position, at which time vision was restored and the arm was allowed to rest on the table until the next trial (intertrial interval 3 s). Subjects wore a vest harnessing a metal plate on the back which was locked between trials to an electromagnet (Warner Electric) affixed to the wall behind the subject. In 60% of randomly selected trials sagittal trunk motion was unrestrained by deactivating the electromagnet at the time of the auditory go signal (free condition). In the remaining 40% of randomly selected trials trunk motion was arrested (blocked condition) by keeping the electromagnet activated during the trial. Because the subjects were instructed to move the trunk by bending at the hips while keeping the torso as a rigid body, the activation of the magnet led to the arrest of the entire torso. Subjects practiced the task ten times in the free-trunk condition only. No knowledge of results was given during the experiment.

Table 1 Clinical characteristics of PD patients: clinical status and medications for Parkinsonian subjects (*A* Amantidine,*B* Baclofen, *E* Eldepryl, *GA* Gen-Amantadine,*L* standard release L-dopa with carbidopa, *LCR*L-dopa controlled release with carbidopa, *LPr*L-dopa standard release with Prolopa, *Me* Metoprolol, *M* Mirapex, *P* Permax, *R* Requip)

Patient i.d.	Sex	Age (years)	Duration of PD (years)	Total UPDRS motor score	Pull test	Rigidity (right arm)	Bradykinesia (right arm)	PD stage (Hoehn and Yahr 1967)	Medication
BM	M	50	5	25	1	2	4	III	LCR, M
SH	F	49	7	30	1	2	5	III	L, B, R
HH	M	71	3	26	1	1	5	III	LCR
AG	M	74	17	35	2	1	5	III	LCR, P
LG	M	84	2	55	1	2	9	III	LPr, GA, Me
ET	M	73	12	33	2	2	7	III	L, A
MC	M	64	17	28	1	1	4	III	L, E, P
EP	F	74	4	30	1	1	6	III	LCR, M
GP	M	71	7	25	0	2	7	II	L, P
Mean	–	67.8	8.2	31.9	1.1	1.6	5.8	–	–
SD	–	11.6	5.8	9.3	0.6	0.5	1.6	–	–

Fig. 1 Experimental set-up



Arm-trunk kinematics were derived from position data obtained by optoelectronic cameras (Optotrak 3010, Northern Digital, sampling rate 200 Hz) localizing six infrared light-emitting diodes attached to the bony landmarks of the sternum, both acromion processes of the shoulders, lateral epicondyle of the elbow, wrist lateral styloid, and index fingertip. Position data were low-pass filtered at 8 Hz and analyzed offline using customized Labview (National Instruments) and Matlab (MathWorks) software. Movement onset and offset were defined as the points at which the tangential hand velocity first exceeded and then fell below 5% of the peak velocity.

Spatial paths

Invariance between the hand paths of the free and blocked conditions was analyzed using a deviation measure. To compute this each hand path was divided into four segments situated between the points representing 0%, 25%, 50%, 75%, and 100% of the trajectory length. Each of the four segments was connected by a line and a *deviation angle* between each adjacent pair of lines was computed (three angles per each trajectory, *angles 1–3*). Also, the initial and final directions of the hand trajectory in external space were computed as the angle between the line of the 1st segment and the x-axis (*initial orientation angle*) and the 4th segment and the x-axis (*final orientation angle*). Differences between the angles of the free and blocked conditions are referred to here as *trajectory divergence*. The spatial variability of the hand paths in the horizontal plane was analyzed by computing the 95% confidence ellipse (Adamovich et al. 2001a; McIntyre et al. 1997) for the free and blocked condition at every 25 ms. The area of the ellipse at 25%, 50%, 75%, and 100% of the trajectory was compared across conditions for invariance.

Spatial errors

Computed were the following: *2D error*, the distance between the final position of the hand (endpoint) and the target in a horizontal plane; *azimuth error*, the angle between the vectors connecting the initial hand position with the target and the initial hand position with the endpoint in the horizontal plane; *radial error*, the difference between the length of the vectors connecting the initial position with the target and the initial hand position and endpoint; *sagittal error*, the difference in distance between the endpoint and the target along the sagittal axis.

Temporal kinematics

The synchrony between the arm and trunk movement was analyzed by comparing the time interval between the onset of hand and trunk motion (*onset desynchrony*) as well as the time interval between the offset of hand and trunk motion (*offset desynchrony*) in the free-trunk condition. For between-condition analysis the hand velocity profiles in the free and blocked conditions were divided into four equal segments representing 0%, 25%, 50%, 75%, and 100% of movement time (MT). The velocity at 25%, 50%, and 75% of MT was compared across conditions for invariance (velocity at 0% and 100% was not compared because it was zero at these times). Also analyzed were *peak velocity*, *time to peak velocity*, and *MT*, the latter being defined as the time between movement onset and offset. The time at which the effect of the perturbation was noted on a kinematic level, the *trunk deviation latency*, was defined as the time interval between trunk movement onset and the time at which the mean trunk velocity profile of the free condition exceeded and remained outside the mean +1 SD of that in the blocked condition.

Joint angles

Elbow flexion/extension was measured as the angle between the line connecting the wrist and elbow markers and that connecting the shoulder and elbow markers. Horizontal shoulder abduction/adduction was measured as the angle between the line connecting the left and right shoulder markers and that connecting the shoulder and elbow markers of the moving arm. Joint excursion was computed as the difference between the maximum and minimum degrees of joint rotation. Invariance between the hand paths of the free and blocked conditions could only be achieved by condition-dependent changes in elbow and shoulder coordination (e.g., the elbow-shoulder profiles must diverge between conditions to produce invariance in hand paths). The latency of the compensatory response therefore was the time interval between the *trunk deviation latency* and the time at which the mean distance between the free and blocked angle-angle curves exceeded 1 SD. The almost orthogonal orientation between the hand paths to T1 and the sagittal trunk motion required the maximal change in joint angles to maintain hand path invariance across conditions. For this reason compensatory latencies could be reliably determined from the changes in the joint angles for movements to T1 but not T2. *Between-condition* comparison of the measured variables was used to estimate the subjects' ability to compensate for the perturbation. Specifically, the presence of invariance between conditions on a given measure suggested that the subject(s) successfully compensated for the perturbation on that given measure. In contrast, *between-group* comparison was useful in determining general motor control deficits related to PD, irrespective of compensatory abilities.

Statistics

Data obtained for the two groups were subjected to a three-way repeated-measure analysis of variance with one "between" factor: group (control, PD) and two "within" factors: condition (free, blocked) and target (T1, T2). For the post hoc analysis we used separate two-way repeated-measure analyses of variance with factors group×target or group×condition. We used the Student-Newman-Keuls test for further post hoc analysis. Variability of performance was analyzed by performing the same procedure on the coefficient of variation (standard deviation/mean) of each measure. Effects on a given measure were considered to be significant if P is less than 0.05. To reduce the probability of type I error in cases of multiple comparisons, the significance level (0.05) was divided by the number of comparisons (five angles for the trajectory divergence and three values for the velocity divergence). Thus the corrected values of significance levels for multiple comparisons were 0.01 and 0.016, respectively. PD subjects' means were also analyzed individually against the mean ±2 SD (95% confidence interval) of the control group. A PD subject's value on a given measure was deemed significantly different if it fell outside this interval. The "Results" section focuses predominantly on measures for which significant differences between the two groups were noted.

Results

Arm-trunk timing

Subjects were required to perform a rapid trunk-assisted arm reach to the remembered target location. The synchrony between the arm and trunk movement was thus compared for the onset and the offset of movement in the unrestrained trials (see "Methods"). The *onset-* and *offset-desynchrony* times between the arm and trunk are shown in Fig. 2 for each trial of each subject. To account for increased variability in the PD group the absolute *onset-* and *offset-desynchrony* intervals were subjected to a three-way analysis of variance [factors: group, target, time (levels: onset, offset)]. A significant group effect was noted, suggesting that PD subjects' hand and trunk motion was less synchronized than in the control group (control vs. PD: 100 vs. 159 ms; $F_{(1,19)}$=6.4, P=0.02). Neither group's hand-trunk desynchrony interacted with target or onset/offset time. A significant main effect of time (onset vs. offset) was noted, suggesting that both control and PD subjects were less synchronized at movement offset than at movement onset. These findings confirm those of Poizner et al. (2000) who demonstrated that PD subjects have timing deficits in coordinating the motions of the arm and trunk during trunk-assisted arm reaching.

The effect of the perturbation on trunk kinematics

Figure 3A, C shows the mean ±SD spatial trunk trajectory of one representative healthy and one PD subject, respectively, for movements to T1. Healthy subjects' mean sagittal trunk displacement was reduced from 19.3 ±2.7 cm in the free condition to 4.2±.8 cm in the blocked condition (across targets). The residual trunk motion in perturbed trials occurred because of the slight compression of the soft tissues by the harness during trunk restraint. Similarly, the mean trunk displacement of the PD subjects was reduced from 17.1±2.3 cm in the free condition to 3.0 ±0.9 cm in the blocked condition. A significant group effect was noted ($F_{(1,19)}$=12.5, P<0.05), suggesting that trunk displacement was hypometric in the PD group. However, no significant group×condition (P>0.05), or group×condition×target (P>0.05) interaction was noted, suggesting that the perturbation had similar consequences on the trunk displacement in the two groups and for the two targets.

Figure 3B, D shows the trunk velocity profiles for one representative healthy and one PD subject, respectively. The peak trunk velocity of both groups was significantly

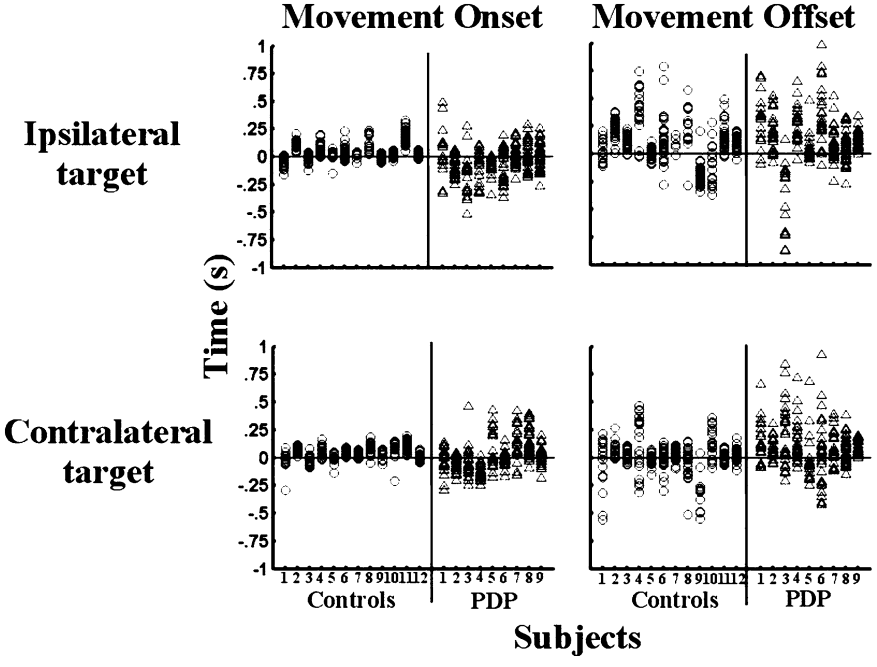


Fig. 2 The timing of arm-trunk coordination in the free-trunk condition for each subject. Delay between the arm and trunk (*vertical axis*, *ms*) is shown for movement onset (*left*) and offset (*right*) for reaches to T1 (*top*) and T2 (*bottom*). A zero value at either onset and/or offset would indicate that the arm and trunk were perfectly synchronized. Positive values indicate that the trunk moved first at onset or finished last at offset. Patients with Parkinson's disease (*PDP*) are numbered in the same order as in Table 1

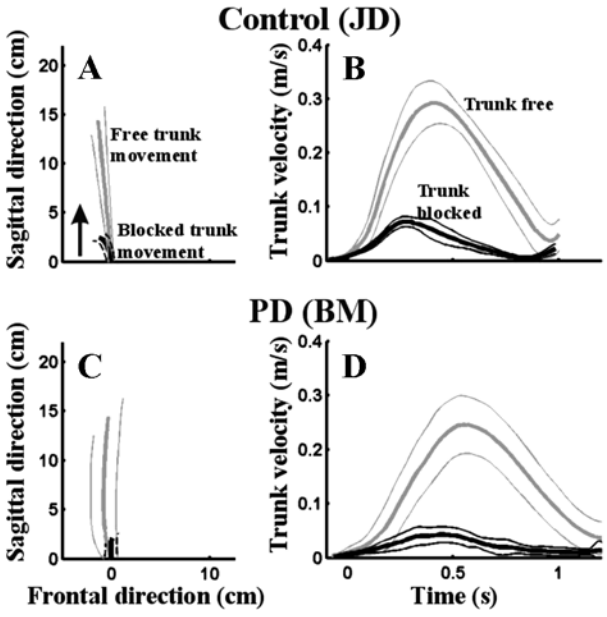


Fig. 3 A healthy subject's (control no. 1) trunk path (**A**) and velocity profile (**B**) during a movement to T1. One PD subject's (no. 1) trunk (**C**) path and velocity profile (**D**). *Gray lines* Free condition; *black lines* blocked conditions

reduced in the blocked compared to the free condition (see Table 2) while overall the trunk movement in the PD subjects was bradykinetic relative to that of the healthy subjects ($F_{(1,19)}$=24.8, P<0.05). Despite these effects trunk movement remained stable for the two targets (group×-target interaction, P>0.05).

The onset of the perturbation was noted on a kinematic level by the divergence of the trunk velocity traces between the two conditions (Fig. 3B, D). In the control group the trunk velocities diverged 82±25 ms after the onset of trunk motion while in the PD group this divergence occurred significantly later (150±110 ms, $F_{(1,18)}$=5.8, P<0.05). The above findings indicate that despite an expected bradykinesia in the PD group the trunk movements were consistent for the two groups and targets. Furthermore, the trunk perturbation led to a significantly reduced trunk motion in both groups, although at a delayed latency in the PD group.

The effect of the trunk perturbation on the hand path

Mean hand paths of each of the 12 healthy subjects as they reached toward T1 are shown in Fig. 4. Shaded regions around the free and blocked trajectories represent 95% confidence ellipses at 25 ms intervals with the final ellipse outlined to illustrate the endpoint variance. Figure 5 shows the same subjects' hand paths toward T2. The invariance between the free and blocked condition hand paths was analyzed using a deviation measure (see methods). In healthy subjects the trajectory divergence between the free and blocked conditions was small. For example, free and blocked condition trajectories did not diverge from each other at the *initial orientation angle* by more than 1.2±1.2°

Table 2 Movement kinematics. Movement kinematics (group mean ±1 SD) for control and parkinsonian subjects for each condition and target (*PV* peak tangential velocity,*t* trunk, *h* hand,*TPV* time to peak velocity,*MT* movement time, *Elbow* total elbow joint variation, *Shoulder* total shoulder joint variation)

	Ipsilateral		Contralateral	
	Blocked	Free	Blocked	Free
Healthy subjects				
2D error (mm)	95.9±68.3	106.1±84.2	43.4±19.8	69.6±31.9
Azimuth (°)	−2.7±8.1	0.4±8.6	−3.5±6.7	1.4±5.5
Radial (mm)	77.7±68.6	88.6±83.3	19.3±34.2	65.9±34.8
Sagittal (mm)	−15.2±64.4	8.1±72.4	−4.5±28.4	47.1±33.0
PVt (mm/s)	111.1±32.6	426.6±99.6	114.6±27.4	391.3±85.3
PVh (mm/s)	1257.2±456.8	1350.2±515.7	571.9±176.5	639.5±188.0
MTh (s)	0.755±0.177	0.757±0.188	0.929±0.244	0.966±0.204
TPVh (s)	0.302±0.087	0.278±0.071	0.345±0.068	0.364±0.071
TPVh/MT (%)	41.6±14.4	38.5±12.6	39.7±13.7	39.3±10.8
Elbow (°)	34.0±15.2	26.8±12.3	45.8±9.9	24.0±8.0
Shoulder (°)	30.0±11.9	56.4±12.7	41.4±8.2	29.1±10.2
PD subjects				
2D error (mm)	58.1±22.0	69.6±33.6	63.3±40.8	60.9±38.0
Azimuth (°)	3.0±4.8	5.7±4.9	−7.9±10.2	−3.0±6.1
Radial (mm)	21.4±33.6	38.2±31.8	−20.1±31.9	38.6±48.1
Sagittal (mm)	21.3±35.2	44.6±39.8	−45.9±49.7	6.4±58
PVt (mm/s)	60.4±20.0	258.2±67.1	60.4±17.4	237.9±41.0
PVh (mm/s)	772.5±490.8	837.9±447.4	385.4±147.7	507.3±191.2
MTh (s)	1.283±0.413	1.199±0.334	1.416±0.336	1.326±0.241
TPVh (s)	0.499±0.156	0.481±0.142	0.512±0.105	0.506±0.114
TPVh/MT (%)	43.8±20.8	42.5±16.6	39±14.3	38.9±10.5
Elbow (°)	29.7±10.3	22.9±5.0	45.6±12.2	30.8±13.3
Shoulder (°)	27.4±7.5	47.9±9.8	47.5±7.1	39.5±11.8

and at the *final orientation angle* by more than 4.9±4.8° for movements to T1. For reaches to T2 these angles were larger, 2.8±1.6° and 13.1±12.9°, respectively. *Angles 1–3* did not exceed the *final orientation angle.* In sum, the relatively small divergence between hand paths for the majority of the movement indicates that the significant and unexpected trunk arrest only had a modest effect on the hand path.

Figures 6 and 7 show the mean hand paths plotted within the 95% confidence ellipses for the nine PD subjects reaching to T1 and T2, respectively. The PD group's mean trajectory divergence was comparable with that of the control group, with not statistically significant differences noted (see Table 2). However, some individual PD subjects showed significantly less overlap between the free and blocked condition trajectories than controls. For movements to T1, the between-condition trajectory divergence at the *initial orientation angle* for PD subjects GP and MC fell outside the 95% confidence interval of the control group, and for subject EP *angle 1* fell outside this range. For movements to T2 trajectory divergence was significantly greater at the *initial orientation angle* for PD subjects AG and MC, and in the case of subject MC for *angles 1* and *2* as well. These findings illustrate that several individual PD subjects were significantly impaired relative to the control group in maintaining invariant hand paths in the presence of an unexpected trunk perturbation.

The effect of the trunk perturbation on endpoint error

In both groups there was a tendency for the hand movement in the blocked condition to undershoot that of the free condition along the azimuth, radial, and sagittal dimensions (see also Table 2). Despite having significantly hypometric movements in both conditions (e.g., radial error, group effect, $F_{(1,19)}$=7.3, P<0.05), no significant effects of the trunk perturbation were noted for the PD group on any error measure (e.g., 2D error, group×-condition interaction, P>0.05). However, it was noted that PD subjects were significantly less accurate than controls when reaching to T2 vs. T1 (e.g., sagittal error, group×-target interaction, $F_{(1,19)}$=5.1, P<0.05). Further post hoc testing revealed that sagittal error did not differ significantly between groups in either the free or the blocked conditions for reaches to T1. In contrast, sagittal errors to T2, while not significantly different between groups in the free condition, were significantly greater in the PD subjects' blocked condition. This indicates PD subjects' endpoint positions for movements to T2 were significantly affected in the trunk-perturbed trials, though not in the unrestrained trials, relative to the control group.

Spatial errors were further analyzed by comparing each individual PD subject against the 95% confidence interval of the control group. None of the PD subjects' spatial errors differed significantly from the control group for movements to T1. For movements to T2, sagittal error for subjects AG, GP, and ET significantly differed from that of the control group in both conditions, and for subject LG in the free condition. The 2D error for PD subjects AG, GP,

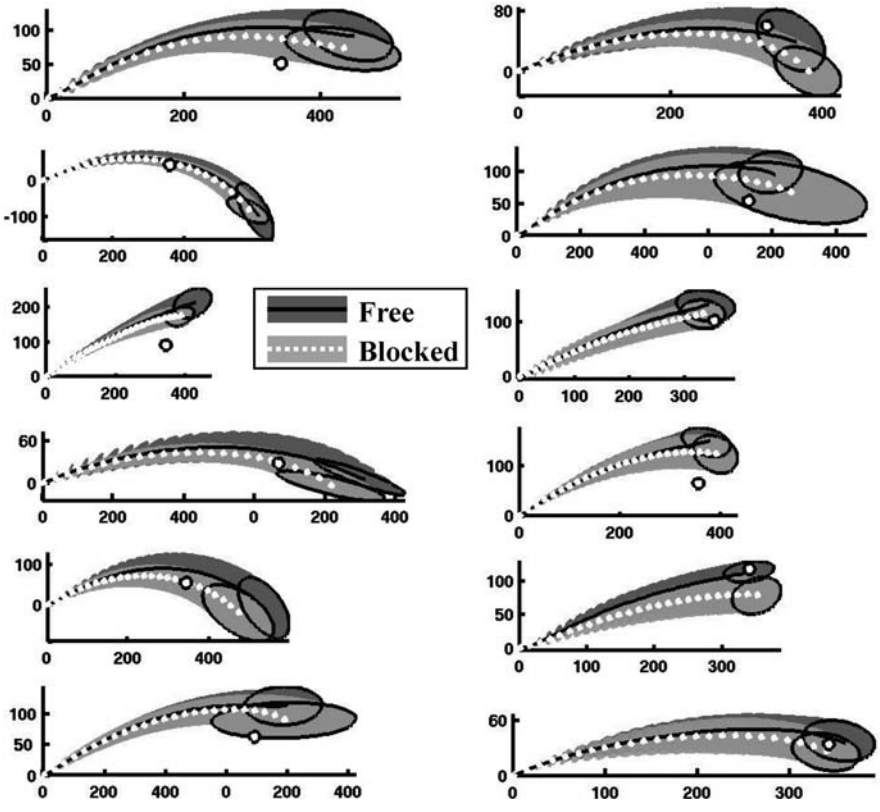


Fig. 4 Hand paths in the horizontal plane of each healthy subject reaching to T1. Shaded regions represent the 95% confidence ellipses of all trials per condition per subject at 25-ms intervals with the final ellipse outlined to show variability in endpoint position. Mean trajectories for free condition (every 50 ms, *circles*) and blocked condition (*solid lines*)

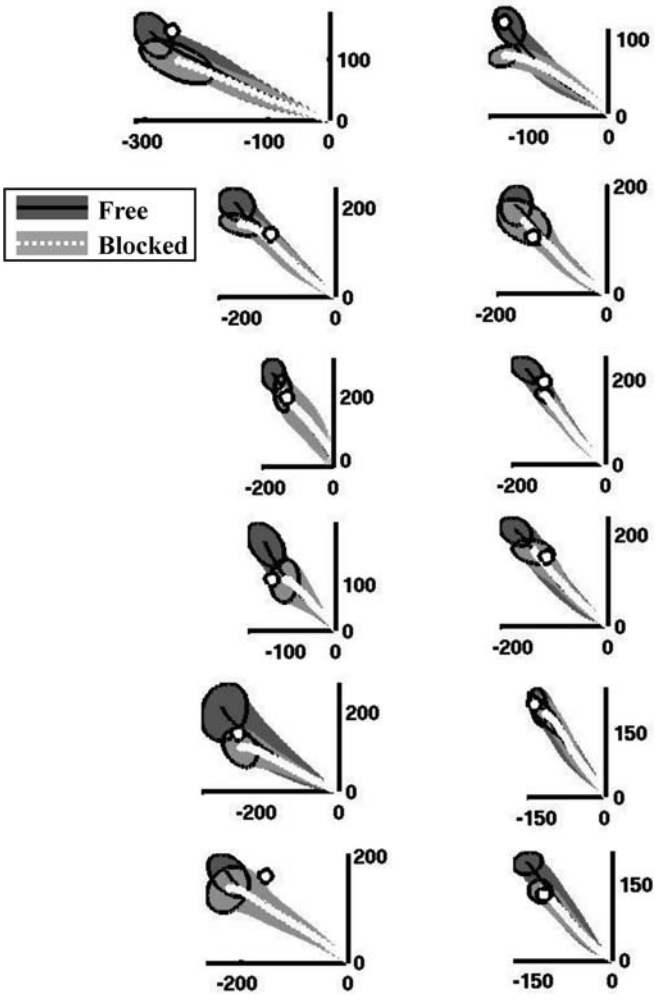


Fig. 5 Hand paths in the horizontal plane of each healthy subject reaching to T2. Shaded regions represent the 95% confidence ellipses of all trials per condition per subject at 25-ms intervals with the final ellipse outlined to show variability in endpoint position. Mean trajectories for free condition (every 50 ms, *circles*) and blocked condition (*solid lines*)

and ETas well as radial and azimuth error for subjects GP and ET was significantly different from that of controls in the blocked but not in the free condition. These findings suggest two deficits. In some subjects a general deficit related to trunk-assisted reaching to a remembered target location (significantly increased error in the free and blocked condition). Second, in other subjects a deficient ability to preserve the endpoint position in a context-dependent manner (significantly increased error in the blocked condition only).

Temporal hand kinematics

As expected, PD subjects were bradykinetic and showed longer time to peak hand velocity and MT relative than controls (see Table 2). However, neither these variables nor the velocity divergence (see "Methods") significantly interacted with the trunk perturbation condition (e.g., group×condition interaction for velocity divergence at 25%, $P>0.05$).

Elbow-shoulder coordination

Reaches to T1 and T2 were performed via elbow extension and horizontal shoulder abduction or adduction, respectively. Mean joint excursion always increased in the blocked-trunk condition to compensate for the reduced motion of the trunk. For example, the elbow joint excursion for movements to T2 in the free and blocked-trunk conditions was 17° and 40°, respectively, for the control group and 26° and 41°, respectively, for the PD group with no differences between groups or conditions (group effect elbow: $F_{(1,19)}=0.06$, $P=0.8$; shoulder: $F_{(1,19)}=0.9$, $P=0.4$).

Joint angle analysis was used in determining the latency of the compensatory response. Invariance in the spatial paths of the hand could only be achieved by condition-dependent changes in elbow-shoulder joint excursion. Compared to reaches toward T2 the almost orthogonal orientation between the hand paths to T1 and the sagittal trunk motion required more substantial changes in joint angles to maintain the same hand trajectory in the presence of trunk arrest. As such, the divergence of shoulder-elbow profiles in the two conditions (compensatory latency) was greater for movements to T1 (compare top panels in Fig. 8). The divergence in the shoulder-elbow profiles of PD subjects occurred significantly later than that of the control group (153.3±60.4 vs. 70±37.2 ms, $t=-3.9$, $P<0.001$). Compensatory changes in the elbow and shoulder angles were initiated within 50 ms in 8 of 12 healthy subjects when reaching to T1 (group range 40–150 ms). In the PD group only three subjects showed compensatory latencies between 40–130 ms and did not significantly differ from those of controls (e.g., see PD subject HH, Fig. 8 middle left panel). In the remaining six PD subjects latencies ranged from 140–250 ms and were significantly delayed relative to those of the controls (e.g., PD subject SH, Fig. 6 bottom left panel).

To determine whether the compensatory response latency was related to movement speed, which might explain the delayed compensatory response in PD subjects, we calculated the correlation of each subject's peak hand velocity with his/her compensatory latency. No significant correlation was noted for either group. Indeed, relative to the control group's hand velocities (free condition to T1, range 0.7–2.5 m/s, mean 1.4 m/s) three PD subjects moved at comparable or faster speeds (GP, 1.2 m/s; LG, 1.1 m/s; ET, 1.8 m/s; PD group range 0.5–1.8 m/s, mean 0.8 m/s). Despite the faster velocities noted in subjects LG, ET, and GP compared to the other PD subjects their compensatory latencies nevertheless remained on the higher end of the range (respectively, 100, 170, and 180 ms; see above). This suggests that bradykinesia alone cannot explain the delayed compensatory responses observed in the PD group.

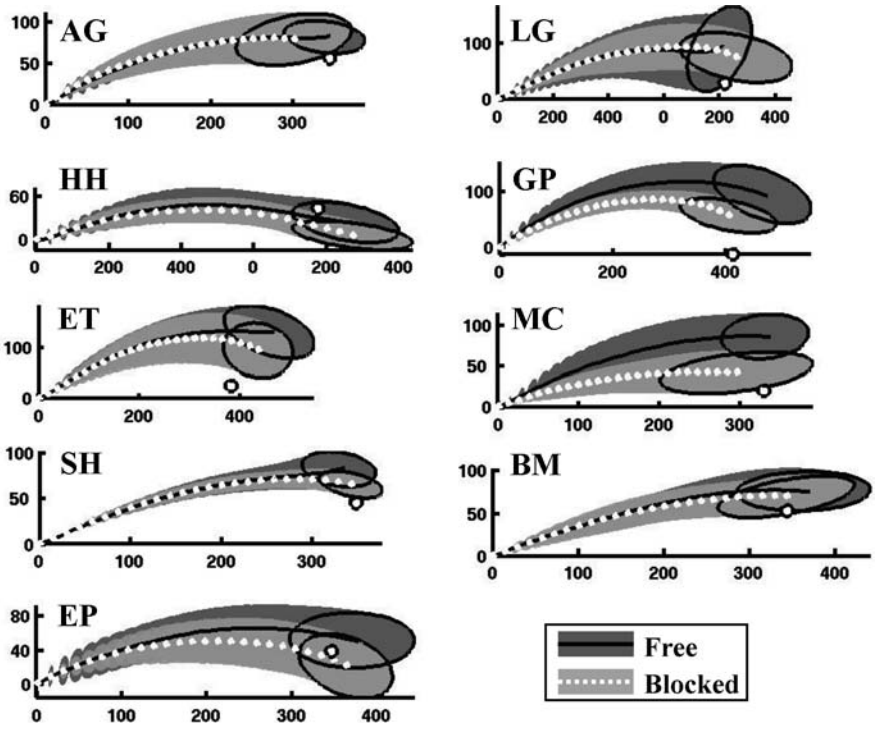


Fig. 6 Hand paths in the horizontal plane of each PD subject reaching to T1. Shaded regions represent the 95% confidence ellipses of all trials per condition per subject at 25 ms intervals with the final ellipse outlined to show variability in endpoint position. Mean trajectories for free condition (every 50 ms, *circles*) and blocked condition (*solid lines*)

Relationship between disease severity and compensatory ability

Due to the heterogeneous performance of the PD subjects and to determine whether their compensatory ability was related to the severity of the disease the correlation of the trajectory divergence at 25%, 50%, 75%, and 100% of the movement with five clinical variables was calculated: duration of disease, UPDRS Pull Test scores, right arm rigidity, right arm bradykinesia (defined as the sum of scores for finger taps, hand opening-closing, and forearm pronation-supination), and the total UPDRS score of the motor section. No significant correlations were noted between the divergence measures and any of theses clinical variables, for either target (e.g., pull test vs. trajectory divergence at 25% for T1: $r=-0.47$, $P>0.05$; for T2: $r=-0.25$, $P>0.05$; and vs. right arm bradykinesia, $r=0.13$, $P>0.05$).

Variability in performance

Spatial variability was analyzed by calculating the area of the 95% confidence ellipses (see Figs. 2, 3) at 25%, 50%, 75%, and 100% of the movement. PD subjects' spatial variability was not significantly greater than that of controls (e.g., group effect and group×condition interaction at 25%: $P>0.05$). The PD group had more variable velocity profiles than the control subjects only in the blocked-trunk condition at 25% and 75% of MT (25% of MT: $F_{(1,19)}=8.7$, $P<0.017$) and for both conditions at 50% of MT. These results suggest that the unexpected reduction in trunk velocity led to a significant destabilization of the hand velocity.

Discussion

Basic findings

The present experiment investigated the role of the basal ganglia in adaptive control by analyzing the compensatory arm responses of PD patients to unexpected perturbations of the trunk during trunk-assisted reaching. The results of this study were: (a) Although responses to the trunk perturbation on the hand paths and spatial errors were similar for the PD and control subjects as groups, individual PD subjects' (four of nine) showed significant context-dependent impairments relative to healthy subjects on various spatial measures. These deficits were noted for reaches directed to both targets. Additionally, the variability in the PD group's hand velocity profiles was significantly greater at the early and late portions of the movement in the blocked but not in the free conditions compared to that of healthy subjects (for reaches to T2). (b) The PD group was significantly delayed in initiating the compensatory arm movement after the trunk perturbation (PD, 153.3 ms; control, 70 ms, for reaches to T1). (c) The PD group showed significantly longer desynchrony intervals between the movement onset of the hand and trunk relative to those of healthy subjects. Our finding that PD subjects' were unable to synchronize multiple segments replicates the findings of Poizner et al. (2000).

The role of basal ganglia in adaptive control

The presence of context-dependent differences in the PD subjects (see above, points a and b), relative to healthy subjects, suggests that the basal ganglia play an important

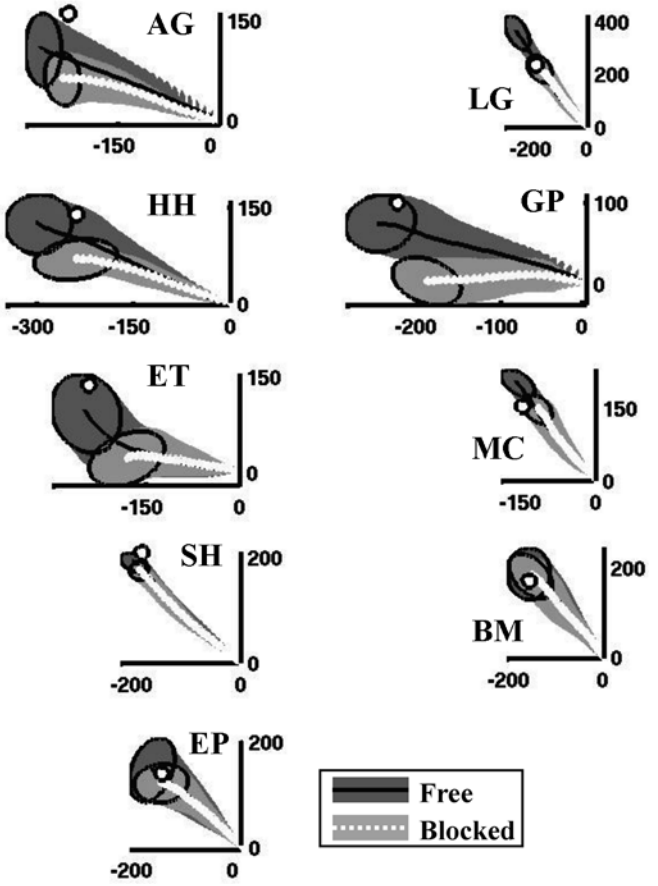


Fig. 7 Hand paths in the horizontal plane of each PD subject reaching to T2. Shaded regions represent the 95% confidence ellipses of all trials per condition per subject at 25-ms intervals with the final ellipse outlined to show variability in endpoint position. Mean trajectories for free condition (every 50 ms, *circles*) and blocked condition (*solid lines*)

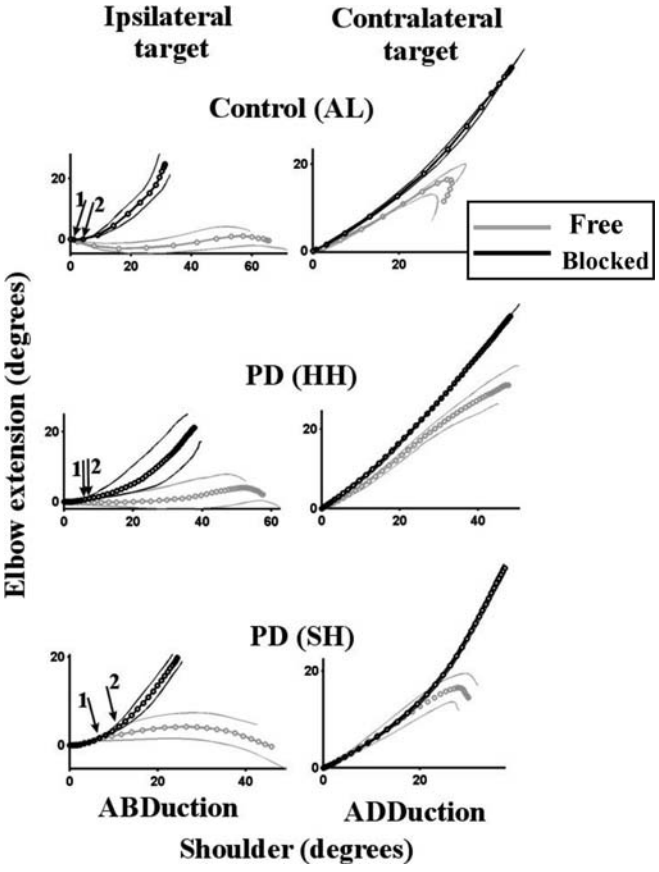


Fig. 8 Elbow-shoulder joint angle profiles for a healthy subject (*top panels*), PD subject for whom the compensatory response latency was in the range of healthy subjects', and PD subject, for whom the compensatory latency was delayed. *First arrow* Trunk deviation latency (effect of the perturbation); *second arrow* divergence between the elbow-shoulder profiles; *left column* movements to T1; *right column* movements to T2; *gray lines* free condition; *black lines* blocked condition. Circles are plotted every 30 ms

role in adaptive control. One alternative explanation of our findings is that the fear of falling led to the observed performance in PD patients. Indeed, it has been demonstrated that even for healthy subjects the fear of a postural threat can lead to changes in anticipatory postural adjustment, effects that may be even more pronounced in individuals with balance disorders (e.g., Parkinson's disease; Adkin et al. 2002). While it remains unclear to what extent this contributes to abnormal balance in PD patients (Chong et al. 1999a, 1999b), it is an unlikely explanation for the results observed in the present study. First, all PD subjects' scores on the pull test component of the UPDRS were comparatively small (see Table 1 and "Methods"). Second, subjects were seated against the wall, on a firm bench, with a table surrounding them on all remaining sides. Third, if fear of falling was a factor, deficits would be expected to be greatest in the free-trunk condition, in which trunk motion was most pronounced—an effect not observed. Fear of falling is therefore not a likely explanation in our study.

Another potential interpretation is that the clinical features of PD (e.g., instability, rigidity, bradykinesia) were responsible for the observed deficits. To investigate this the correlation between several components of the motor section of the UPDRS and the divergence measure was analyzed. No significant correlations were noted, suggesting that while these may have contributed to the general (between-group) differences, they were at the least not the only factors contributing to deficits in adaptive control.

A third potential interpretation, particularly regarding the significantly delayed compensatory latencies observed in the PD group is that the reduced attention in PD subjects led to these delays. We attempted to minimize this effect by providing all subjects with a "prepare" cue prior to each trial. Doing so has been shown to reduce delays in reaction time by 82–85% in stage II or III PD patients (Yanagisawa et al. 1993).

Rather, the most probable interpretation of our results is that the basal ganglia participate in adaptive control of movement. Electrophysiological recordings in nonhuman primates support the involvement of the basal ganglia in adaptive control. Turner and DeLong (2000) have shown that corticostriatal neuronal activity onsets with approx. 60 ms latency after mechanical perturbations of the elbow

or shoulder. Additional processing time (20–30 ms) to account for each iteration of the cortical-basal ganglia-cortical loop (Brooks 1997) and for the descending signals to reach the effectors (approx. 25 ms; Brunholzl and Claus 1994) would amount to a latency of about 105–115 ms. Accounting for the abnormally prolonged medium and long latency reflexes that involve subcortical and cortical circuits (Beckley et al. 1993; Bloem et al. 1995a, 1995b) would thus yield compensatory latencies consistent with those observed in our PD subjects.

In conclusion, this study investigated adaptive control of upper limb movements to motor perturbations in healthy subjects and PD patients. Given the context-dependent motor deficits observed in the PD subjects on our task it is suggested that the basal ganglia are involved in the generation of compensatory reactions related to arm-trunk coordination.

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