Control of multidigit grasping in Parkinson’s disease: effect of object property predictability

Marco Santello, a,* Lisa Muratori, b and Andrew M. Gordon b

a Department of Kinesiology and The Harrington Department of Bioengineering, Arizona State University, Tempe, AZ 85287-0404, USA
b Department of Biobehavioral Sciences, Teacher’s College, Columbia University, New York, NY 10027, USA

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Abstract

We examined the extent to which subjects with Parkinson’s disease (PD) modulate normal fingertip forces during five-digit grasping based on the object’s center of mass (CM). We also tested the effect of trial-to-trial predictability of CM location on the distribution of all fingertip forces relative to thumb force. Ten right-handed subjects with PD (OFF and ON medication) and 10 healthy age-matched control subjects participated. Subjects lifted a manipulandum that measured normal forces exerted by each digit. The CM location was changed from trial-to-trial either in an unpredictable (random) or predictable (blocked) order. Discriminant analysis and information theory were used to quantify the extent to which force-sharing patterns could be discriminated as a function of CM location. All subjects modulated fingertip normal forces as a function of CM location regardless of its predictability, although larger forces were employed when its location was unpredictable. However, in controls, normal force modulation of individual fingers to the object’s CM location occurred over a greater range of forces when the CM location was predictable than when it was unpredictable. In contrast, subjects with PD exhibited a similar force modulation to CM location regardless of its predictability. There was a clearer discrimination of force-sharing patterns when the CM location was predictable for controls but not for subjects with PD OFF medication. Medication improved the time course of normal force modulation to CM location. These results indicate that subjects with PD maintained the ability to modulate individual fingertip forces to the object’s physical properties. Nevertheless, subjects with PD did not benefit from the a priori knowledge of object CM location to the same extent as controls. These findings support the notion that PD affects the ability to use anticipatory control mechanisms.

Keywords: Parkinson’s disease; Isometric force; Hand; Grasp; Motor control

Introduction

Impaired hand function can be among the symptoms most affecting activities of daily living in individuals with Parkinson’s disease (PD). The bases for the impaired function are not well understood. In the last decade, there have been some kinematic and kinetic studies of hand motor control in PD. Remarkably, many of these studies have shown that while there are subtle differences between the performance of subjects with PD and neurologically healthy individuals, the overall hand motor control is minimally affected for simple tasks. For example, during reach-to-grasp of an object, there may be greater variability of grasp parameters (Alberts et al., 2000) and reduced coupling and fine tuning of the hand and arm movements in time (e.g., Bennett et al., 1993; Castiello et al., 2000), but the overall kinematic parameterization (e.g., aperture of the thumb and index finger) in subjects with PD does not substantially differ from that of age-matched control subjects (e.g., Bonfiglioli et al., 1998; Gentilucci and Negrotti, 1999; Tresilian et al., 1997). Similarly, during the grasping and lifting of small objects using precision grip, subjects with PD have prolonged transitions between the various phases of the grip–lift and release movement (Gordon, 1997, 1998; Ingvarsson et al., 1997). However, once the main force increase is initiated, all subjects display appropriate parallel coordination of the normal and tangential forces and appropriate anticipatory

Abbreviations: PD, Parkinson’s disease; CM, center of mass; UPDRS, Unified Parkinson’s Disease Rating Scale; MMSE, Mini Mental State Examination; SME, Sensorimotor Efficiency.

* Corresponding author. Department of Kinesiology, PEBE 107B, Orange Street, Arizona State University, Tempe, AZ 85287-0404. Fax: +1-480-965-8108.
E-mail address: marco.santello@asu.edu (M. Santello).
and sensorimotor control based on the object’s physical properties (Gordon et al., 1997; Ingvarsson et al., 1997).

The subtle deficits observed during these tasks, requiring the use or measurement of only the index finger and thumb, do not explain the poor hand function observed in PD. However, most objects that we routinely manipulate require coordination of all five digits. Subjects with PD are known to have problems with the simultaneous control of multiple effectors (e.g., Almeida et al., 2003; Benecke et al., 1986; Schwab et al., 1954). In fact, one recent study showed that during multidigit reach-to-grasp, subjects with PD exhibit a delayed specification of hand preshaping to objects of different shapes (Schettino et al., 2004). Thus, the study of whole-hand reach-to-grasping showed movement deficits not observable by the study of two-digits.

Only recently has attention been given to the force coordination during whole-hand grasping in healthy individuals (e.g., Kinoshita et al., 1995; Rearick and Santello, 2002; Reilmann et al., 2001; Santello and Soechting, 2000; Shim et al., 2003; Zatsiorsky et al., 2002a,b, 2003). For both two- and five-digit grasping, the total force contribution of the finger(s) opposing the thumb (force-sharing pattern) must be parcelled such as to obtain equilibrium of forces and moments (Santello and Soechting, 2000). However, unlike two-digit grasping, this equilibrium can be achieved by a large number of force-sharing patterns when employing five digits. For example, if an object’s center of mass (CM) is located on the thumb side (see slot no. 1 in Fig. 1), the equilibrium could be achieved by having the little finger account for the majority of normal force opposing the thumb. Another possible solution would be for the little finger to counteract the thumb normal force by sharing the total opposing force with one or more of the other fingers. Despite the large number of solutions, subjects consistently selected a small set of sharing patterns that reflect the object’s properties (Rearick and Santello, 2002; Reilmann et al., 2001; Santello and Soechting, 2000). Thus, subjects simultaneously coordinate multiple digit forces based on the task demands in a consistent manner.

Little is known about multidigit force coordination during grasping in subjects with PD, and given the increased complexity, there may be deficits above and beyond those previously reported by studies of two-digit grasping. One recent study (Rearick et al., 2002) found that the action tremor often observed in individuals with PD (cf. Forssberg et al., 2000) disrupts the phase coordination of digit normal forces. In contrast, all subjects maintained force amplitudes and sharing patterns that were comparable to age-matched controls. Nevertheless, that study did not examine the effect of variation of the object’s physical properties, which would require precise modulation of forces at individual digits. Thus, it is unknown whether the forces and the sharing pattern of individuals with PD are matched to object characteristics. Furthermore, recent evidence suggests that the extent to which force-sharing patterns can be discriminated as a function of CM location is reduced when the CM location is unpredictable on a trial-to-trial basis for healthy subjects (Rearick and Santello, 2002). It is unknown whether the force-sharing pattern discrimination would be affected by predictability of the CM location in subjects with PD during five-digit grasping. The effect of predictability may be particularly important as subjects with PD have been shown to have an impaired ability to use information in advance for the planning of movement (see Gauntlett-Gilbert and Brown, 1998 for review).

The ability to exert individuated fingertip forces during five-digit object lift and hold is preserved in subjects with PD (Rearick et al., 2002). Since subjects with PD have difficulty with the simultaneous coordination of movement components (e.g., Benecke et al., 1986; Ingvarsson et al., 1997; Schwab et al., 1954), the extent to which subjects with PD can modulate individual fingertip forces to the object’s properties may be diminished. The aim of the present study was to determine (a) whether subjects with PD modulate their force-sharing patterns based on the object’s CM location, and if so, (b) at what time point during the task they do so, and (c) whether this is dependent on medication state. Based on the increased complexity of this task compared to two-digit grasping, we hypothesized that the ability to scale individuated forces to change in object CM location would be impaired.

We also tested the effect of trial-to-trial predictability of the CM location on the force-sharing pattern. We hypothesized two potential outcomes: (1) If subjects with PD scale the fingertip forces based on the object’s properties as they do during two-digit grasping (Gordon et al., 1997; Ingvarsson et al., 1997), the force-sharing pattern would reflect the CM location to a larger extent when it is predictable than when it is not (Rearick and Santello, 2002); or (2) Subjects with PD may employ a default sharing pattern irrespective of CM location even when object CM location can be predicted on a trial-to-trial basis. Finally, we examined the effects of dopaminergic medication upon the coordination of force-sharing patterns. Since there appears to be dopaminergic-sensitive and dopaminergic-resistant parameters of movement (e.g., Blin et al., 1991; Bloem et al., 1996; Caligiuri et al., 1992; Castiello et al., 2000; Ingvarsson et al., 1997; Johns et al., 1993; cf. Gordon and Reilmann, 1999), we hypothesized that dopaminergic medication would not have a uniform effect on tested parameters.

**Methods**

**Subjects**

Ten right-handed subjects with idiopathic PD (4 males, 6 females; mean age, 61.3 years; range, 45–73 years) and 10 healthy age-matched right-handed controls (7 males, 3 females; mean age, 60.9 years; range, 44–75 years) participated in this experiment. All subjects gave their informed consent according to the declaration of Helsinki and proto-
cols were approved by the Teachers College, Columbia University Institutional Review Board.

Table 1 provides a clinical description of each subject with PD. All subjects were referred and screened by a certified neurologist. Subjects with PD were stages I–III Hoehn and Yahr and had symptoms that were either predominantly right-sided or bilateral and symmetrically distributed. The mean disease duration was 5.9 years, and none showed medication-induced dyskinesia. Exclusion criteria for all subjects were (1) arthritis, (2) orthopedic or visual problems that would interfere with the task, (3) other coexisting chronic neurological diseases, (4) sensory deficits, defined as >5 mm on two-point discrimination, (5) dystonia, (6) significant rigidity, (7) active psychosis, (8) upper extremity weakness, (9) significance cognitive impairments (a score <24 on the Mini Mental State Examination, MMSE), and (10) coexisting autonomic symptoms (“Parkinson’s plus” condition).

All subjects were undergoing medical treatment (Table 1). Subjects with PD were tested early in the day before their initial dose of medication (12 h following their last dose, i.e., practically defined OFF state). They were also tested in the ON state, defined as 1 h after their normal medication dosage. We tested half of the subjects with PD in the OFF medication state first, and the other half ON medication before OFF (i.e., on separate days). Six subjects were taking L-DOPA replacement (Sinemet), while four were only taking other anti-parkinsonian medication. To determine whether there were differences between subjects who were taking Sinemet and subjects who were not, we initially included medication type as a factor in all of our statistical analyses. Medication type did not affect any of the task measures or interact with any of the factors (see below). No subject showed motor complications due to the therapy that interfered with the task. Therefore, for all subsequent analyses, all subjects with PD (n = 10) were pooled.

Table 1
Clinical description of subjects with Parkinson’s disease

<table>
<thead>
<tr>
<th>Patient</th>
<th>Sex</th>
<th>Age (years)</th>
<th>Duration (years)</th>
<th>Medication (mg/day)</th>
<th>Stage (H&amp;Y)</th>
<th>UPDRS ON</th>
<th>UPDRS OFF</th>
<th>MMSE</th>
<th>Average grasp (kg)</th>
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H&Y = stages I–V according to Hoehn and Yahr scale, UPDRS = items 18–31 (motor examination) or the Unified Parkinson’s disease rating scale, MMSE = Mini Mental State Examination.
Experimental procedures

We measured normal grip forces using an apparatus (Fig. 1) consisting of five force sensing modules (FR1010 force sensors, Futek, Laguna Hills, CA), one for each digit. Within each module, we measured the force normal (Fx) to the front face of the module to it. The average accuracy of the sensors was ± 0.2 N.

The front face of each module consisted of a smooth metal vertical surface and the modules were fixed to two side walls, one for the thumb and one for the fingers. The center-to-center distance between adjacent modules was 2 cm, the thumb module being aligned with the module for the middle finger (Fig. 1). The point of application of fingertip forces was effectively constrained by the vertical dimension of each force sensor, that is, 1.6 cm for each finger and 2.8 cm for the thumb. This dimension roughly corresponds to the width of the fingertips and thumb fingerrad. The width of the manipulandum, that is, the distance between the front faces of the finger and the thumb modules, was 6.25 cm. Each sensor was sampled at 1 kHz.

The output of the grip device was acquired by an analog-to-digital converter card (DAQ 6023E, National Instruments; 12-bit resolution). Movement of the object was recorded with an electromagnetic position-angle sensor (Polhemus Fastrack, VT; 0.075-mm resolution). This sensor was used to define grasp phases (i.e., onset of object lift, hold, and replacement) as well as to measure yaw, pitch, and roll to ensure that the orientation and horizontal and vertical displacement of the device during the task were identical for all subjects. The Polhemus data was stored and analyzed in a flexible computer system (SC/ZOOM, Department of Physiology, Umeå University). We tested the effect of the object’s center of mass (CM) location on the coordination of grip forces by repositioning a mass on the device. The mass (0.4 kg) was added by inserting a metal block at four equidistant locations at the base of the apparatus (slots 1–4, Fig. 1). This resulted in four horizontal CM locations: −1.3, −1.1, +0.1, and +0.4 cm, respectively, relative to the center of the apparatus. The vertical location of the CM was 13.3 cm above the base. The external torques exerted by the added mass relative to the midpoint of the base of the device were +0.12 and +0.04 N m (counterclockwise) and −0.04 and −0.12 N m (clockwise) when the weight was added at slot 1–4, respectively. The weight exchanges were performed out of subjects’ view and the location of the added mass at the base of the device was blocked from view by a cardboard strip. The total weight of the apparatus was 1.195 kg.

Experimental tasks

All subjects washed their hands before the experiment. Subjects were seated at a standard table with their dominant forearm in a neutral posture parallel to the floor. Since the primary focus in this study was to examine multidigit force control during the lift and hold, all subjects were asked to position their hands on the apparatus, that is, place individual digits on separate force sensors, before starting the task. They were further instructed not to exert force until informed to grasp and lift the apparatus, allowing us the opportunity to examine the development of digit forces. Compliance with this requirement was verified both online during data collection and quantitatively offline during data analysis. After an auditory “go” signal was given, subjects were instructed to lift the apparatus at a self-selected pace to the height of an adjacent vertical marker (approximately 5 cm), hold it for 3 s (timed by the experimenter), and then to lower it to its original location. Subjects were instructed to hold the manipulandum aligned with the vertical during the hold phase.

The CM location was changed from trial to trial in an unpredictable order (random) or across blocks of trials (blocked). In both predictability conditions, subjects performed a total of 20 trials, that is, 4 CM locations × 5 trials. Rest periods of 2 min were interspersed among the trials to avoid fatigue. The unpredictable condition was presented to the subjects before the predictable condition to prevent subjects from becoming familiar with the CM locations. To change the CM location, the object was moved beyond view of the subjects. Since subjects could not anticipate the CM location, for the predictable conditions, subjects performed one practice trial before performing a block of five trials. Trials were repeated if subjects sensed that a finger made contact with more than one of the force sensing modules (which were separated by gaps, Fig. 1) or the experimenter observed that this had happened. If this occurred during the unpredictable condition, both the preceding and the incorrect trial were repeated. Overall, <1% of all trials were repeated.

Grasp phases

Despite the experimental instructions (see above), some subjects from the control group and the PD group exerted small forces while waiting for the go signal, though the object remained stationary. Since the object’s actual CM location can be inferred only after object lift, these small forces do not afford additional sensory cues on how to distribute fingertip normal forces. Thus, for the present study, we confined our analysis to two periods: from the onset to the end of vertical lift (lift phase) and from the end of the lift until the subjects began to return the object to the table (hold phase).

Statistical analysis

We examined the force-sharing patterns by quantifying the modulation of normal forces exerted by each finger to maintain grip forces in equilibrium; that is, the sum of all finger normal forces equals the normal force exerted by the thumb. Before performing statistical analysis, the duration of the lift and hold phase was normalized for each trial to
allow comparison across trials, subjects, and predictability conditions. Due to the requirements for equilibrium of normal forces, variations in the amplitude of finger normal forces can also be due to variations in thumb normal force. Therefore, to eliminate the effect of thumb normal force, we divided the normal force exerted by the index, middle, ring, and little fingers (Ix, Mx, Rx, and Lx, respectively) by the thumb normal force. We could then examine specifically the relative contribution of each of the four fingers opposite the thumb, that is, force-sharing pattern. Absolute normal forces were also analyzed as described below.

Amplitude of finger normal forces

The effect of the CM location on normal forces exerted by each digit was quantified by computing the mean force averaged across the hold period. The force variability was assessed by first computing the standard deviation (SD) of the normal force exerted by each digit averaged across time for each grasp phase (i.e., object lift and hold) and across trials. To allow comparison across digits exerting forces of different amplitudes, the SDs associated with the mean force value at each time point were divided by the mean value to express force variability in normalized form, that is, as coefficient of variation (CV). We then defined normal force intertrial variability as the CV values averaged across all time points during object lift and hold. These two time periods were analyzed separately as they are characterized by different mechanical constraints and hence might elicit different force coordination patterns. During object lift, the forces exerted by all digits rapidly increase as the object is lifted to prevent object slip, whereas object hold require maintaining approximately constant forces until the object is released.

Discrimination of force-sharing patterns

We used discriminant analysis (Johnson and Wichern, 1992) and information theory to quantify the extent to which force-sharing patterns could be discriminated as a function of object’s CM location. The procedures used to compute the discriminant functions and to allocate each trial to a given object have been described in detail elsewhere (Santello and Soechting, 1998). Briefly, discriminant functions maximize the ratio of the between groups variance to the within groups variance. In this case, a “group” consists of the four finger normal forces normalized to thumb normal force associated with each of the four CM locations. A given trial is then allocated to the group it is closest to in discriminant space (a jackknife procedure was used; Johnson and Wichern, 1992). This analysis was performed at each quartile of the two phases, that is, 1%, 25%, 50%, and 75% of the lift duration and 1%, 25%, 50%, 75%, and 100% of the hold duration (end of object lift coincides with onset of the hold phase). The results of the discriminant analysis were used to construct a confusion matrix (Johnson and Phillips, 1981; Santello and Soechting, 1998, 2000). If no relationship existed between the device configuration and the force patterns used, the SME index would be zero while a perfect correspondence would be represented by the maximum value of the SME index (100%).

Analysis of variance (ANOVA) with repeated measures was performed on the variables (a) through (c) to assess the effect of changing CM location and predictability of object CM location. We performed a group (controls vs. PD ON; controls vs. PD OFF) × CM location (4) × predictability condition (unpredictable vs. predictable) × digit (5) ANOVA on the absolute normal force. Since the normal forces of the four fingers must, by definition, sum to equal that of the thumb, the normal force at any of the digits is uniquely determined by the sum of the other four digits. Therefore, the effective number of independent degrees of freedom is n − 1, that is, four normal forces. Thus, for analysis of force-sharing patterns, we removed the middle finger forces from the data set before performing statistical analyses. This finger was chosen since theoretically, its force is modulated the least to changes in CM location; that is, it is directly aligned with the thumb. Nevertheless, we compared the results of these analyses to additional analyses with removal of each of the other four digits separately and the results were essentially the same. Lastly, for the analysis of force-sharing pattern discrimination, we performed a group × predictability ANOVA. To assess differences in performance ON and OFF medication, we performed separate ANOVAs including medication as a within-subject factor.

Results

We quantified the effect of CM location and its predictability on the fingertip forces and the temporal evolution of forces in controls and subjects with PD. Overall we found that the average force modulation in subjects with PD was similar to that found in controls. However, clear differences were seen between these two subject groups in the temporal evolution of fingertip forces as a function of object CM location. Furthermore, subjects with PD were able to modulate forces to object CM location to a greater extent in the ON than in the OFF medication state. These findings are described in detail below.

Coordination of multidigit normal forces

Fig. 2 shows the normal forces exerted by the thumb, index, middle, ring, and little fingers (T_x, I_x, M_x, R_x, and L_x, respectively) when the CM location was predictable and
unpredictable on a trial-to-trial basis (left and right column, respectively) for an age-matched control subject and a subject with PD OFF and ON medication (top, middle, and bottom row, respectively; CM location no. 3).

The normal forces developed gradually at all digits until the object lift occurred. Note that in some instances, the subjects started to exert forces before the go signal to lift the object was given (see Methods). All normal forces increased throughout object lift (approximately 1 s, denoted by blue portion of horizontal line, Fig. 2) and then reached a plateau during the hold phase (denoted by red portion of horizontal line, Fig. 2). The object was held for up to 3–4 s after which the device was returned to its original location. No systematic difference was found between the two subject groups in the orientation of the device relative to the vertical during the hold phase. This might suggest that subjects with PD were able to coordinate fingertip forces relative to thumb forces as required by the task in a similar fashion as controls. Nevertheless, this performance may have been accomplished through a wide range of force-sharing patterns (see Introduction). Specifically, changes in normal forces exerted by an individual finger due to changes in the CM location can be compensated by changes in normal forces exerted by any of the remaining digits, the only constraints being equilibrium of normal forces, that is, thumb normal force must equal the sum of normal force exerted by all fingers. Below, we examine in detail group differences in the force-sharing patterns.

Fig. 2. Normal forces during grasp, lift, hold, and release. Each panel shows the normal forces exerted by the thumb (Tx, black traces), index finger (Ix, red traces), middle finger (Mx, blue traces), ring (Rx, green traces), and little finger (Lx, pink traces) during one representative trial of grasp, lift, hold, and release of the device with the mass added at slot no. 3 (see Fig. 1). Force traces are aligned with respect to object lift 1 s on the time-axis. The blue portion of the horizontal bars indicates the lift phase of the trial while the red portion indicates the hold phase. Data are from one control subject (top row) and one subject with PD (subject no. 5) OFF and ON medication (middle and bottom rows, respectively) when the CM location was predictable and unpredictable (left and right column, respectively).
subject groups and not significantly affected by CM location predictability. However, as described below, differences were found in the modulation of normal forces to CM location within each predictability condition.

**Effect of CM location on normal force modulation**

When the CM is located on the thumb side of the device (i.e., slot 1, Fig. 1), maintaining the object vertical requires smaller forces at the index finger and larger forces at the little finger to counterbalance the counterclockwise torque, and vice versa when the CM is located on the finger side (i.e., slot 4, Fig. 1). Lastly, the ring finger would be adjusted more than the middle finger but not to the extent of the index and little fingers.

The proportion of the normal force exerted by each of the fingers during the hold phase depended on the location of the center of mass of the device, in accordance with the experimental design. As expected, changing CM location elicited different distributions of normal forces exerted by the individual digits (Fig. 3). Specifically, shifting the CM location from the thumb to the finger side of the device caused larger forces at the index finger and smaller forces at the little finger, whereas the middle and ring fingers did not show a clear trend. These patterns, resulting from the mechanical constraint of maintaining the object vertical, were common to both controls and subjects with PD in both medication states (Fig. 3). Individual fingers exerted significantly different normal forces ($P < 0.001$) invariably, with the normal forces being progressively smaller from the thumb to the little finger. Each digit was affected to a different extent by changes in object CM location (finger × CM interaction; $P < 0.001$), with the thumb and the index finger being the digits characterized by the largest force modulation. No group differences were found in the amplitude of absolute forces exerted by each digit.

Analysis of data pooled across all digits and predictability conditions from controls and subjects with PD OFF medication revealed a significant increase in normal forces due to changes in object CM location ($P < 0.05$), with the average forces being higher when the CM was located on the finger side (i.e., slot no. 4, Fig. 1). Changes in CM location did not significantly affect the amplitude of normal forces pooled across all digits and predictability conditions from controls and subjects with PD ON medication. Medication did not have a significant effect on force modulation as a function of CM location (Fig. 3). Lastly, when the CM location was unpredictable, some digits exerted larger normal forces than when it was predictable, with the largest and smallest differences being at the index and ring fingers (+10% and +5%, respectively; finger × predictability interaction; $P < 0.01$).

In summary, when considering the force amplitude averaged over time across the entire hold phase, subjects with PD and controls scaled fingertip forces to the CM location in a similar fashion. Despite these similarities, between-group differences emerged when force modulation was analyzed for grasping the object with a predictable versus an unpredictable CM location and as a function of time as described below.

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**Fig. 3.** Normal forces as a function of object center of mass. The normal forces exerted during the hold phase for each center of mass (CM1 to 4) are shown for when the CM location was predictable and unpredictable (top and bottom row, respectively). Each bar indicates the normal force exerted by the thumb, index, middle, ring, and little fingers (T, I, M, R, and L, respectively) averaged across subjects (± standard deviation).
Effect of object CM location predictability on normal force modulation

For the control group changes in CM location elicited a clearer modulation of normal forces when the CM location was predictable than when it was unpredictable. A decrease of up to 32% versus an increase of 21% for the predictable and unpredictable conditions, respectively, was found relative to the force exerted while holding the device with the CM located on the thumb side (CM1, Fig. 1). Differences in force modulation due to predictability of object CM location were not as clear in subjects with PD. The extent of force modulation in subjects with PD ON and OFF medication was approximately 21% regardless of predictability of CM location, that is, a force modulation similar to that found for control subjects when the CM location was unpredictable.

Data pooled across all CM locations showed a tendency for the generation of larger forces when the CM location was unpredictable (Fig. 4). Both controls and subjects with PD either ON or OFF medication exerted larger normal forces (on average, +11%) when it was unpredictable (main effect of predictability, \( P < 0.05 \) invariably), this effect being stronger at some fingers (e.g., thumb, Fig. 4) than others (finger \( \times \) predictability interaction; \( P < 0.001 \)).

Effect of CM location on force-sharing patterns

To further quantify the simultaneous modulation of all fingertip forces as a function of object CM location and its predictability, we calculated an index (sensorimotor efficiency index, SME) reflecting the extent to which each CM location elicited a distinct force-sharing pattern over time (see Methods). Fig. 5 shows the SME index averaged across subjects for each experimental group and predictability condition during object lift and hold.

Although the SME index changed significantly as a function of time from the onset of object lift to the end of the hold phase (\( P < 0.001 \) invariably), important differences in the time course of the force-sharing pattern discrimination were found between predictability conditions for each subject group. Controls and subjects with PD ON medication (Figs. 5A, C) demonstrated behaviors that were statistically similar between groups and qualitatively similar to those reported previously for healthy subjects (Rearick and Santello, 2002). Specifically, (1) force-sharing patterns can be

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Fig. 4. Normal forces when the CM location was predictable and unpredictable. The normal forces exerted during the hold phase are shown for when the CM location was predictable and unpredictable. Each data point indicates the normal force exerted by the thumb, index, middle, ring, and little fingers (T, I, M, R, and L, respectively) averaged across centers of mass and subjects (±standard deviation).

Fig. 5. Information transmitted during the grasp. The sensorimotor efficiency (SME) index was computed at equally spaced time intervals during the lift and hold phase. From top to bottom, data are averages of all subjects (±standard errors of the mean) from the control group, subjects with PD OFF and ON medication, respectively. The vertical dotted line indicates the end of lift phase/onset of hold phase.
discriminated early in the task (i.e., object lift, main effect for time \( P < 0.001 \)); (2) the number of force-sharing patterns is smaller than the number of object CM locations (i.e., SME < 100%); (3) the extent to which force-sharing patterns can be discriminated as a function of CM location remains relatively constant from the late part of object lift to the end of object hold (\( P > 0.05 \)); and (4) during object hold, the predictable CM condition was characterized by a clearer discrimination of force-sharing patterns than the unpredictable CM location condition (Fig. 5) (predictability, \( P < 0.001 \)), with the discrimination increasing more over time in the predictable condition (predictability \( \times \) time interaction, \( P < 0.01 \)). Thus, controls and subjects with PD responded to predictable changes in the CM location by adopting a larger number of force-sharing patterns than when the CM location could not be predicted on a trial-to-trial basis.

Subjects with PD in the OFF medication state did not benefit as much as controls from a priori knowledge of CM location (Figs. 5B and A, respectively). This is indicated by a smaller between-predictability conditions difference than those found in the control group (Figs. 5B, 6) (predictability \( \times \) group interaction, \( P < 0.05 \)), particularly during the hold phase (time \( \times \) group interaction, \( P < 0.05 \)). Nevertheless, the SME increased over time when the CM was predictable (predictability \( \times \) time interaction, \( P < 0.05 \)).

Although there was not an overall direct effect of medication on the SME (\( P < 0.12 \)), the comparison between subjects with PD ON and OFF medication revealed a main effect of time (\( P < 0.05 \)) and predictability (\( P < 0.05 \); Figs. 5C, 6). Furthermore, there was a significant interaction between time and medication (\( P < 0.05 \)). This interaction is important as it indicates that medication played an important role in allowing a finer temporal modulation of fingertip forces to the actual CM location.

In summary, the discrimination of force-sharing patterns as a function of CM location was higher when the location was predictable. In addition, predictability had a greater influence on discrimination for controls than subjects with PD OFF medication. The effect of medication was alterna-

tively demonstrated by the appropriate scaling of fingertip forces by subjects with PD ON medication.

**Discussion**

Subjects with PD appropriately scaled their fingertip forces to the object’s CM location as required by the experimental design. However, unlike the two-digit grasping studies earlier reported, several important features of force modulation in subjects with PD were different from those exhibited by controls. Specifically, controls employed a wider range of forces when the object CM location could be predicted than when it could not be predicted on a trial-to-trial basis. In contrast, the overall force modulation in subjects with PD OFF medication was not enhanced by predictability of the object CM location. This suggests that subjects with PD did not take advantage of a priori information about the object’s CM location in a predictive fashion to the same extent as the controls. We also found that medication affected the temporal evolution of force-sharing patterns, with subjects with PD ON medication being able to (a) exert grip forces throughout object lift and hold in a quantitatively similar fashion as controls, and (b) modulate the forces over time to a greater extent than in the OFF medication state. These findings and their implications are discussed below.

**Control of force-sharing patterns during multidigit grasping**

Neurologically healthy subjects adopt a few consistent force-sharing patterns when grasping an object with five digits despite the large number of patterns that would ensure a stable object grasp. These force patterns do reflect, however, the object’s properties such as the center of mass (Santello and Soechting, 2000) and weight (Reilmann et al., 2001). Another interesting feature of multidigit force-sharing patterns is that they emerge at—or shortly after—object lift, and are maintained relatively unchanged throughout object hold. This behavior is reminiscent of anticipatory control of grip forces described for two-digit grasping (e.g., Gordon et al., 1993; Johansson and Westling, 1984, 1987, 1988; Salimi et al., 2000, 2003), indicating a predictive component in the selection of grip forces before object properties can be inferred through tactile feedback.

The gross features of multidigit grasping control are not affected by PD (Rearick et al., 2002). Specifically, force amplitude and variability, as well as the temporal evolution of force-sharing patterns, when grasping an object with an invariant CM location have characteristics that are similar to those exhibited by controls. (At a finer level of grip force coordination, however, subjects with PD who have action tremor do show characteristic anomalies in the force synchronization patterns but only at action tremor frequencies; Rearick et al., 2002.) Since this prior work did not address the modulation of grip forces to the object’s CM location,

Fig. 6. SME index when the CM location was unpredictable and predictable. The sensorimotor efficiency (SME) index averaged throughout the lift and hold phases is shown for each subject group and predictability condition. Data are averages of all subjects (±standard deviation).
one of the goals of the present study was to assess the extent to which the ability of modulating fingertip forces to object properties is affected by PD. We hypothesized that the ability to scale individuated forces might be impaired by the disease. This could have resulted in a uniform scaling of all fingertip forces rather than a more independent control of forces exerted by each digit. The present results indicate that subjects with PD in both medication states were able to scale individuated fingertip forces to the object’s CM location in a similar fashion to controls (Fig. 3), even though important differences were found when analyzing the modulation of forces to object CM location in the time domain (Figs. 5; see below). The changes in object CM location used for the present study have been shown to be sufficient to elicit modulation of individual fingertip normal forces in neurologically healthy subjects (Rearick and Santello, 2002; Santello and Soechting, 2000). It is possible that larger differences between controls and subjects with PD, however, would have emerged had there been a greater variation of CM location and/or external torques.

Unpredictable versus predictable presentation of object CM location

Due to delays in feedback, object grasping and lifting heavily rely on anticipatory control of grip forces, which is based on a priori knowledge of the object’s physical properties such as the weight, texture, and center of mass (e.g., Gordon et al., 1993; Johansson and Westling, 1984, 1987, 1988; Salimi et al., 2000, 2003). Thus, a requirement for appropriately scaling the fingertip forces is the maintenance of working memory. Data from five-digit grasping show that neurologically healthy subjects use a smaller number of force-sharing patterns when object center of mass cannot be predicted on a trial-to-trial basis (Rearick and Santello, 2002), that is, they tend to use a default strategy, in which they take advantage of the redundancy in digits rather than finely scale individual fingertip forces to the object’s CM location. The present data confirm this result in controls and extend it to subjects with PD. Another similarity between the two subject groups was that when the CM location was unpredictable, larger forces were elicited than when the object CM location was predictable (Fig. 4). This finding might also be interpreted as a default strategy to ensure that forces of sufficient amplitude are exerted to prevent object slip, that is, an increase in the safety margin (e.g., Johansson and Westling, 1984). However, regardless of object CM location predictability, subjects with PD were characterized by force scaling over a more limited range of forces than controls. Furthermore, differences due to object CM location predictability in force scaling were more pronounced for the control group than for the PD group.

The more limited force scaling for the subjects with PD OFF medication in the predictable condition suggests impairments in anticipatory control. Despite successive experience with an object with a fixed CM location, these subjects did not take advantage of the information pertaining the CM location gained during previous lifts to the same extent as the controls did. The lack of predictive control during multidigit grasp based on the CM location is in contrast to the preservation of predictive control based on object weight during two-digit grasp (Gordon et al., 1997). It is conceivable that there are separate control mechanisms for these two object features (Salimi et al., 2000) (see below). It is also conceivable that improved control would emerge with additional practice since subjects with PD are known to have impairments in motor learning (e.g., Haaland et al., 1997; Harrington et al., 1990; Krebs et al., 2001).

The impairments in predictive control based on object CM location are in agreement with reaction time studies suggesting that subjects with PD have impairments in the capability to use information in advance for the planning of movement (Bloxham et al., 1984; Evarts et al., 1981; Harrington and Haaland, 1991; Pullman et al., 1990; Sheridan et al., 1987; Stelmach et al., 1986; see Gauntlett-Gilbert and Brown, 1998 for review). Similarly, precues providing instructions regarding the direction of forthcoming movements were not utilized as well during movement execution in unmedicated subjects with PD, though medication remedied this impairment (Johnson et al., 2003). Furthermore, subjects with PD have been shown to have delays between the initiation of transport and manipulation components during prehension in predictable situations, but a response more similar to healthy controls when reactive control is required; that is, following spatial perturbation of the object (Scarpa and Castiello, 1994). It is conceivable that there is an impaired ability to maintain a given motor plan (or in this case a representation of an object’s physical properties) against competing alternatives (Haaland et al., 1997; Robertson and Flowers, 1990) or an impairment in the acquisition of motor set, whereby existing motor plans are modified to suit the current task (Frith and Done, 1986). Likewise, the impaired predictive control may be caused by impairments in working memory (e.g., Ghilardi et al., 2003; Owen et al., 1992). These behaviors would be consistent with the hypothesis that the interplay between the basal ganglia and prefrontal cortex is important in the selection of the best movement specification from a set of alternatives (Adamovich et al., 2001; Saint-Cyr, 2003). The beneficial effect of medication on the force modulation under predictable conditions in this study, as well as improvements in reach-to-grasp following medication shown in earlier studies (Castiello et al., 2000), further support this suggestion. Our findings suggest that the impairments in utilization of advance information may have direct consequences for performing functional, skilled manipulatory behaviors during everyday tasks, and that medication may partially ameliorate them.

It should be noted that in the unpredictable condition, subjects could have potentially used sensory information about the actual CM location acquired after object lift onset.
Such information could have been subsequently used to modulate force-sharing patterns as a function of the object center of mass, that is, a modulation that does occur in the predictable condition. However, both controls and subjects with PD adopted the same strategy characterized by fewer force-sharing patterns than object CM locations, a behavior that was not significantly affected by medication (Fig. 6). Medication, however, did have an effect on the temporal evolution of force-sharing patterns (Figs. 5B–C), allowing subjects with PD ON medication to perform a finer scaling of fingertip forces to the object CM location than in the OFF medication state. More work is required to establish the extent to which the medication state directly affected the sensorimotor processes associated with perceiving object CM location and adapting the force-sharing patterns accordingly.

A study on two-digit grasping revealed that subjects with PD are able to use information about object weight—acquired through previous lifts—to control the rate of force development at object lift on subsequent trials (Gordon et al., 1997) to a similar extent as controls. The present results from the predictable condition indicate that subjects with PD OFF medication did not use such a predictive mechanism. This discrepancy between these results might be due, in part, to the different constraints imposed by the two tasks, that is, changes in object weight versus changes in object CM location. The retrieval and implementation of sensorimotor memory associated to object weight—requiring a symmetric partition of thumb and finger forces when grasping with two digits—might be computationally more challenging for five-digit grasping, a task requiring finer individuation of fingertip forces across all digits. Furthermore, five-digit grasping is less constrained than two-digit grasping as force-sharing patterns do not need to be finely tuned to the object’s properties. Hence, subjects with PD might have chosen to use a solution (default force-sharing pattern) that worked for all CM location during the predictable condition, a choice that would not be successful for two-digit grasping.

Conclusions and clinical implications

Previous work on simpler grasping tasks (i.e., with two digits) revealed few deficits in fingertip force regulation. The results of the present study, however, indicate that during more complicated grasping tasks requiring the simultaneous coordination of forces exerted by all digits, subjects with PD show more substantial impairments in force control. Since most activities of daily living require use of all five digits, the impairments in multidigit force control may have greater consequences for the successful completion of these activities. Furthermore, subjects with PD did not benefit from the a priori knowledge of object CM location to the same extent as controls. This is in agreement with the notion that PD affects the ability to use anticipatory motor control mechanisms. Despite these impairments, the present study showed that these deficits were partially ameliorated with medication. This suggests that this task may be useful in quantifying precise changes associated with disease progression and modification. This possibility requires further investigation.

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