Coordination and Control of Forces during Multifingered Grasping in Parkinson’s Disease

Matthew P. Rearick, George E. Stelmach, Berta Leis, and Marco Santello

Department of Kinesiology, Arizona State University, Tempe, Arizona 85287

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In this study, we focused on how subjects with Parkinson’s disease (PD) grasp and lift with five-digits of the hand. This task provided the opportunity to simultaneously examine (a) the coordination of multiple segments (i.e., digits), (b) the sequencing of multiple tasks (i.e., force development, object lift, and hold), and (c) the control of force output. We found that PD patients coordinated and controlled five-digit forces comparable to that of age-matched controls. Specifically, these groups developed and maintained similar force amplitudes and force sharing patterns across all grasping phases. In addition, PD patients demonstrated similar levels of variability both within and across trials. In the frequency domain, however, some differences were observed across groups, especially in PD patients exhibiting obvious action tremor (AT) at a single modal frequency. In these subjects (four of nine PD patients), there was a systematic disruption, i.e., a phase-shifting away from \( \frac{\pi}{2} \), in-phase force synchronization patterns normally observed between digits. This disruption typically occurred at and around the AT frequency, while at many other frequencies synchronization patterns were maintained. The composite of these findings implies that although global features observed in five-digit grasping in PD patients are preserved, more subtle aspects of the coordination between digits, as revealed by frequency domain analysis, are not. These results are discussed in relation to the neural mechanisms that might underlie physiological synchronization of forces and its pathological disruption.

Key Words: Parkinson’s disease; tremor; grasping; finger force synergies; force control; human hand.

INTRODUCTION

Parkinson’s disease (PD) is typically characterized by bradykinetic movement in both gross and fine motor tasks, often coupled with rigidity of musculature and resting, postural, and/or action (AT) tremor (17, 27, 36, 37). Research also suggests that PD patients have difficulty controlling multiple limb segments (2, 20, 35), coordinating two or more motor tasks (4, 32), and controlling the rate of force development in isometric force output (33, 34). All this work points toward malfunction in the basal ganglia (16) and its cortical intermediaries (8).

Research on grasping using precision grip, i.e., with the thumb and index finger, has shown that PD patients have several general impairments in function. Specifically, they tend to exhibit a slowing of the preloading phase, as well as a stepwise development of grip force (13, 20). In addition, PD patients tend to produce excessive forces, both in peak and in static grip force (13). However, Ingvason et al. (20) reported no differences in peak force amplitude between PD subjects and controls.1

It is important to note that other features of grip control—such as the coupling of grip (normal) and load (tangential) forces described by many grasping studies (14, 21, 29)—are preserved in PD patients. In fact, this coupling is maintained regardless of changes in (a) an object’s weight, (b) coefficient of friction between hand and object (20), or (c) anticipation of increases in load during object hold (18).

By definition, an equal and opposite force is needed between the thumb and index finger in order to maintain static equilibrium and a balance of forces and moments as an object is lifted and held. When grasping with five digits, the same physical requirement exists between the thumb and fingers. However, how the four fingers share the total force—equal and opposite to the thumb—is indeterminate (30). This provides an interesting coordination problem for the central nervous system (CNS), a dilemma that might be particularly challenging for a system that has deteriorated neurologically.

1 This discrepancy in the results might have resulted from methodological differences. Ingvason’s grip apparatus was free to move in any dimension. In Fellows’ paradigm, the grip device was located on a low-friction track, allowing for movement only in the vertical plane.
Several recent studies (28–30) suggest that the four fingers opposite the thumb parcel force in systematic ways. First, a consistent rank order, determined by the total normal force contributed by each digit, is generally observed. This is often referred to as the force sharing pattern and is typically ordered from most to least force as such: index, middle, ring, and little fingers. Second, there tends to be significant covariation across all digits during the force-rise, lift, and hold phases, implying that a common mechanism exists for force development and maintenance. Last, there is a strong in-phase (–0°) coupling among all five digits across a large span of the functional force range (0–10 Hz), regardless of object properties, i.e., center of mass location (30), predictability of upcoming object properties, and handedness (28). Summarily, these findings suggest that stereotypical strategies exist for controlling five digits during grasping.

In the present study, we focused on how PD patients grasp and lift with five digits of the hand. This task provided us with the opportunity to simultaneously examine (a) the coordination of multiple finger forces opposite the thumb (i.e., controlling multiple body segments), (b) multiple tasks (i.e., sequencing of force development, object lift, and hold), and (c) force control across all digits of the hand (i.e., rate of force development, amplitude of force, and force variability). Previous work indicates that these features are impaired in PD patients, although to a different extent across tasks (20, 32, 35).

In particular, we wanted to determine whether PD patients were capable of coordinating and controlling multiple digits systematically. The question was whether they could develop and maintain a consistent force sharing pattern and covariation of fingertip forces throughout the three phases of the grasp and lift, as has previously been described for neurologically normal individuals (28–30). We also asked whether PD patients would be more variable, both within and across trials, in their control of force output, as has been reported for various tasks such as orofacial movements (1) or force tracking (31). Last, due to the nature of AT and its unclear etiology (17), we wanted to stringently examine a large range of frequency components (0.5 to 17 Hz) from grip forces for all five digits.

We wanted to determine whether PD patients would retain a physiological synchronization pattern, i.e., approximately 0° in-phase coupling, across all digits of the hand (28, 30), as has also been suggested in two-digit grasping in PD patients (17). However, an alternative outcome might be that AT would cause a disruption in these synchronization patterns. This might be brought about by AT’s prominent oscillating characteristics, ultimately resulting in a general entrainment in digit forces, i.e., a phase-shifting toward or away from –0°. The implications of such a disruption in the force coupling among digit pairs, if found across a large range of frequencies, might lead to compensatory strategies, such as the production of excessive grip forces (13) to ensure object stability.

**METHODS**

### Participant Selection and Screening

Nine idiopathic Parkinsonian (PD) patients (mean age: 69.9 years, SD = 8.7; seven males and two females), and nine controls (69.9 years, SD = 9.0; seven males and two females) were included in the study. Patients eligible to participate had a history of levodopa responsiveness and the presence of two of the four cardinal symptoms of PD (tremor, bradykinesia, rigidity, postural instability) (6). All participants had normal or corrected vision and unrestricted movement in the upper extremities. Participants met a cutoff score of 27 on the Mini-Mental State Exam (15), indicating that they were free of dementia. None of the control subjects had a history of any CNS disease.

All patients were tested after an overnight fast of at least 12 h from their last intake of PD medication resulting in a drug minimum state, i.e., “off” medication. Patients scores ranged from 2 to 3 on the Hoehn and Yahr stages (19) and from 26 to 38 points on Subscale III (motor exam) of the Unified Parkinson’s Disease Rating Scale (UPDRS) (12). The average of summed scores for Subscale III UPDRS items that tested upper limb (extremity) performance (questions 20–25) was 15.9 ± 2.6 for the dominant limb (8 right hand, 1 left hand [JO]). Severe resting tremor was quantified by a score of 3 or greater on the UPDRS motor exam. A summary of patient characteristics is presented in Table 1.

For both experiments, each subject completed the 10-point Edinburgh Inventory to quantify their handedness (26) on a +100 (maximally right-handed) to −100 (maximally left-handed) laterality quotient scale (LQ). For controls, LQ from all right-handed subjects (n = 9) ranged from +71.4 to +100 (mean: 91.2, SD: ±11.6). For PD patients, it ranged from +50 to +100 (mean: 78.1, SD: ±23.5) for all right-handed subjects (n = 8). In addition, one PD subject was left-handed (LQ: −89.5). All subjects gave their informed consent and the protocols were approved by the Institutional Review Board of Arizona State University.

### Experimental Procedures

We measured normal and tangential grip forces using an apparatus (Fig. 1A) consisting of five force sensing modules (FR1010 force sensors, Futek, Laguna Hills, CA), one for each digit. Within each module, one sensor measured the force tangential to the front face of the module and the other the force normal to it. All sensors were (a) calibrated with weights ranging from
0.1 to 2 kg, (b) checked for voltage drift throughout the testing session, and (c) evaluated periodically for accuracy of the calibration. Cross-talk between the sensors was eliminated by means of a calibration matrix. The average accuracy of the sensors was 0.2 and 0.1 N for normal and tangential forces, respectively. The front face of each module consisted of a smooth 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 modules was 2 cm, the thumb module being aligned with the module for the middle finger (Fig. 1A). Each sensor was sampled at 1 kHz. The weight of the apparatus was 0.795 kg. The width of the manipulandum, i.e., the distance between the front faces of the fingers and the thumb modules, was 6.25 cm.

Experimental Tasks

Since the primary focus in this study was to examine multidigit force control during the lift and hold and not the reach, all subjects were asked to position their hands on the apparatus, i.e., 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, therefore allowing us the opportunity to examine the development of as well as static force control. Compliance with this requirement was verified both online during data collection and quantitatively offline during data analysis. After a “go” signal was given, subjects lifted the apparatus at a self-selected rate to a height of ~5 cm. Subjects held it for approximately 3 s and then lowered it to its original location.

Subjects were instructed to hold the manipulandum aligned with the vertical during the hold phase. To ensure that subjects complied with this requirement, a tilt program was developed to evaluate the force output from the thumb and the summed force output from all four fingers. If an equal and opposite force was produced between them, as is necessary in order to keep the object in a vertical position, then there should be no difference in the force exerted by the thumb and the sum of forces exerted by each finger, respectively. However, if a subject tilted the object, via either wrist pronation or supination, then this difference would be nonzero. It should be noted that, overall, all subjects (controls and PD patients) were very good at maintaining the object along the vertical. Nonetheless, when excessive tilting was identified (i.e., a difference >1.0 N), the trial was either repeated or removed from further analysis.

The trial was repeated when (a) the subject sensed that a finger made contact with more than one of the force sensing modules (which were separated by gaps; Fig. 1A) or (b) the experimenter visually determined that the subject placed a digit on more than one sensor. Each subject was required to grasp and lift the grip apparatus 10 times with the dominant hand. Rest periods of 2 min were interspersed among the trials to avoid fatigue.

Grasp Phases

The grasp was divided into four periods: from the time at which the last digit’s normal force crossed a threshold to onset of lift (1; “force-rise phase”); from onset of lift to onset of device hold (2; “lift phase”); from onset to end of device hold (3; “hold phase”); and from end of device hold to release of the device (4; “release phase”). Our analysis focused on the first three grasp phases. The beginning and the end of the lift phase were signaled by a pressure switch. The end of the lift phase was defined as the time at which the first derivative of the sum of the vertical forces crossed below a threshold (0.001 N/s) and remained below it for 300 ms.
A similar criterion was used to define the end of the hold phase. These criterion times were also checked visually by the experimenter to ensure continuity in the period chosen as the hold phase from trial to trial and across subjects.

Statistical Analysis

One-way analysis of variance (ANOVA) was performed on data from the hold phase to assess the effect of group membership (control or PD) on the amplitude of force at each digit. We analyzed normal forces in two ways: (a) absolute force and (b) force normalized to thumb normal force. The analysis of absolute force at all digits was performed to assess whether PD patients tended to grip harder than controls, i.e., as a possible means of compensation due to the expected lack of manual dexterity. In addition, as the sum of finger normal forces must equal the magnitude of thumb normal force when the object is held statically, 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 (I, M, R, and L, respectively) by the thumb normal force. We could then examine specifically the relative contribution of each of the four fingers opposite the thumb, i.e., force sharing pattern.

Temporal Evolution of Force Sharing Patterns

To examine the temporal evolution of force sharing patterns, we determined the mean grip forces for each digit throughout the entire force-rise, lift, and hold phases. After time normalizing data sets within each grasp phase to compute a mean and SD of 10 trials, we selected five discrete time points for analysis: onset of load forces (onset of positive rise in the sum of tangential force exerted by all digits), onset of lift, and three time points during the hold (i.e., hold onset, midhold, and hold end). We then determined the rank order of digits based on the force they exerted. We performed repeated-measures ANOVA for each digit with the amplitude of normal force at each of the five time points as the within-subjects factor and group membership (control or PD) as the between-subjects factor.

Intra- and Intertrial Variability

We assessed whether groups (control or PD) had similar intra- and intertrial variability of the normal force exerted by each digit. Intra-trial variability was calculated as follows. For each trial, the standard deviation and mean amplitude of the normal force during the hold phase were calculated for each digit. Intra-trial variability was quantified as the coefficient of variation (CV), i.e., the standard deviation divided by the mean.

The overall intratrial variability was the average CV across the 10 trials. Intertrial variability was calculated by averaging across 10 trials the normal force exerted by each digit throughout the hold phase. We defined intertrial variability as the coefficient of variation, i.e., standard deviation of the normal force across 10 trials divided by the mean normal force.

Temporal Covariation of Normal Forces: Regression Analysis and Fourier Analysis

Linear regression analysis was performed to assess the extent to which normal forces exerted by pairs of digits covaried at each of the three grasp phases (force-rise, lift, and hold). A one-way ANOVA was performed on correlation coefficients (r) from each grasping phase (n = 3) and each digit pair (n = 10) in order to assess the effect of group membership (control or PD) on the degree of covariation. To better illustrate force covariation at particular frequencies, we performed a fast Fourier transform analysis (FFT) on the forces exerted during the hold phase over a period of 2 s (i.e., 2000 samples). This analysis was performed for each trial and digit.

From the FFT, the phase difference between two digits was calculated at each frequency by subtracting the phase response (as determined by calculating the arctangent of the ratio of the imaginary and real components of the Fourier transform) for one digit from that of another, e.g., phase difference $= \phi_{1} \Phi_{2} - \phi_{2} \Phi_{1}$. This yielded a value indicative of the temporal relationship between the force responses of two digits at a particular frequency. For example, if these two digits produced force at similar times, i.e., squeezed together, then their phase difference was $\pm 0^\circ$, in-phase. If the digits produced force at alternating times, i.e., one squeezed after a certain delay from the other, then their phase difference was $> 0^\circ$, out-of-phase.

For each subject, the first step in the frequency domain analysis was to determine whether the distributions of phase differences at each frequency bin and each digit pair were nonrandom, i.e., whether phase differences tended to cluster at a particular angular value across trials. If this were the case, it would indicate the existence of a fine temporal regulation of normal forces, as revealed by consistent relationships (i.e., phase difference) between them. Indeed, previous work (28, 30) has shown that phase differences computed from forces exerted by all pairs of digits tend to cluster at very small angular values, i.e., $\pm 0^\circ$, indicating a tendency to apply forces in a synchronous fashion. The phase difference ($\phi$) was measured for all pairs of digits ($n = 10$) and for each trial ($n = 10$) over
frequencies between 0.5 and 17 Hz in 0.5-Hz frequency bins (n = 34). For each distribution (n = 10 observations per digit pair), three parameters were computed: the length of the mean vector (r), the mean angle of the sample (φ), and the angular deviation (s) (3). The parameters φ and s are analogous to the mean and standard deviation used in linear statistics. Therefore, φ indicates the mean phase difference of the distribution and s indicates the amount of dispersion around φ.

These parameters were derived from the x- and y-coordinates associated with each phase difference, i.e., \( \cos \beta \) and \( \sin \beta \), respectively. The means of x- and y-coordinates (x and y) were used to compute the length of the mean vector (r), as \( (x^2 + y^2)^{1/2} \), and the mean angle of the sample (φ) is computed as \( \arctan (x/y) \). The parameter s is computed as \( [2(1-r)]^{1/2} \). The value of r ranges from 0 to 1, where 0 indicates that phase differences are evenly distributed and 1 indicates that all data are clustered at one angular value; these two extreme cases being defined as random and nonrandom distributions, respectively.

Figure 1B shows an example illustrating the contrast between a random and nonrandom distribution. Randomness of phase difference distributions was tested using the Rayleigh test, which is based on the amplitude of the parameter r. If r is large (i.e., close to 1), then the distribution tends to be clustered at a particular mean angle. Conversely, if r is small, then the distribution tends to be less defined, i.e., more scattered throughout the range of possible angular values.

Coherence Analysis

Coherence analysis was performed on the force exerted by each digit pair (n = 10) during the hold phase in order to determine the degree of correlation, i.e., the percentage of shared variance (analogous to \( R^2 \) in regression analysis in the time domain), between the force signals at each frequency (38). The squared coherence yields responses between 0 and 1, these values indicating linear independence and dependence of two signals, respectively. Often coherence analysis is used to determine the degree of association between an input signal (x) and an output signal (y) (22, 23). In our case, however, we were interested in the relationship between two output variables, i.e., normal force exerted simultaneously by pairs of digits. In calculating the auto and cross-spectral estimates of our data at each frequency, we used a block size (FFT length) and window (Hanning) of 2000 points, respectively. We calculated coherence on each frequency bin (n = 34) and trial (n = 10). We examined the average of 10 trials. Our sampling rate was 1 kHz, which yielded coherence values at 0.5-Hz frequency bins.

RESULTS

Normal and tangential forces from four fingers in opposition to the thumb for both PD and control subjects exhibited a similar temporal formation to that previously described for precision grip tasks (14, 20, 21) and five-digit grasping (28–30). Figure 2 shows the normal forces exerted by the thumb, index, middle, ring, and little fingers for four subjects, two PD (KW
and HW) and their respective controls (HL and EB). The derivative of the sum of all tangential forces, shown at the bottom of each panel, was used to define the beginning and end of the hold phase (see Methods). The force traces are aligned with respect to the lift of the device (dashed vertical line, B). Dotted lines A and F indicate onset and offset of force, respectively, whereas E indicates object placement on the switch. Data shown are the average of all 10 trials, low-pass filtered at 20 Hz (Butterworth, sixth order).

Some PD patients did, however, exhibit exaggerated action tremor oscillations that appeared to be superimposed on a well-defined grip (normal) and load (tangential) force coupling during lift and hold (17). Figure 3 shows normal force traces, as well as force-rate profiles, for the thumb and index finger across the force-rise (A–B), lift (B–C), and hold (C to the end of the force trace) phases from a single trial for three different subjects (two PD and one control). KW (PD) shows a classic stepwise normal force profile during the force-rise phase (A–B), which is further illustrated in the force-rate traces. Interestingly, this prominent oscillation observed in both the thumb and the index for KW continues on throughout the lift and hold as well, even though the appropriate amount of force output has been obtained to lift and hold the grip apparatus. In contrast to KW, PD patient RJ does not show a stepwise force-rate profile, as their force-rate profile is nearly bell-shaped and very similar to a control subject’s profile (AW). Overall, we observed that the step-
wise force-rate profiles—as reported by other authors (13, 20)—appear to be AT-specific (e.g., see also Fig. 5 bode plot, KW; (17)) rather than PD-specific. Indeed, not all PD patients, specifically those without a prominent AT (e.g., see also Fig. 5 bode plot, RJ), exhibited a stepwise development of force output.

Normal Force Amplitude and Variability

Normal forces were analyzed in two ways: (a) absolute amplitude of force exerted by each digit and (b) force exerted by each of the four fingers normalized with respect to thumb normal force (see Methods). The absolute amplitude of force across digits ranged from 6.8 ± 2.4 to 1.1 ± 0.5 N (thumb and little finger, respectively) in PD and 7.3 ± 2.6 to 1.5 ± 1.1 N (thumb and Little finger, respectively) in controls. The normalized forces across the four fingers ranged from 49.4 ± 9.0 to 13.6 ± 3.6% (index and ring finger, respectively) in PD and 48.1 ± 12.4 to 16.1 ± 6.4% (index and ring, respectively) in controls. We found no significant difference between groups for either absolute amplitude or normalized amplitude within any digit (P > 0.05). This indicates that PD and control subjects produce similar (a) overall force amplitudes at each digit as well as (b) finger forces relative to the thumb, i.e., force sharing pattern.

In addition, the coefficient of variation of normal force amplitudes (see Methods) was not significantly different between PD and controls either within or across trials. Within-trial variability ranged from 0.05 ± 0.02 to 0.12 ± 0.07 (index and little fingers, respectively) in PD and 0.05 ± 0.03 to 0.09 ± 0.07 (thumb and ring fingers, respectively) in controls. Across-trial variability ranged from 0.09 ± 0.03 to 0.18 ± 0.07 (index and ring fingers, respectively) in PD and 0.08 ± 0.02 to 0.22 ± 0.10 (thumb and ring fingers, respectively) in controls. This implies that in five-digit grasping subjects with PD produce consistent forces within each digit.

Emergence of Force Sharing Pattern across Discrete Grasping Phases

We addressed the question of when force sharing patterns, i.e., the percentage of thumb force exerted by each digit, used to hold the object emerge over the course of the task for both PD and controls. We analyzed data across the first three consecutive phases of grasping for each experimental condition (see Methods). We found that force sharing patterns tended to emerge very early in the task, i.e., during the force-rise phase. This finding was common to both groups, with some idiosyncratic variation across subjects (see below).

Figure 4A shows data from four subjects, two PD (BJ and ME, left column) and their respective controls (HM and AW, right column). When the digits started producing normal force, fingers sometimes exerted larger forces than the thumb, all forces being very small (<1 N). The proportion of thumb normal force that fingers contributed then quickly decreased and fluctuated until lift occurred. Throughout the lift and hold phase, the force sharing pattern tended to remain relatively unchanged. Occasionally, small fluctuations occurred, resulting in either a switch in the rank order (see Fig. 4A, subject HM, middle and little fingers, force-rise phase) or an overlap, i.e., no difference in the force exerted by two or more digits (see Fig. 4A, subject AW, middle, ring, and little fingers, hold phase). Nevertheless, these idiosyncratic differences among all subjects, i.e., regardless of age or disease, were characterized by small changes in force amplitude (~5–8% of thumb normal force). Therefore, force amplitude rank order was generally set before the object was lifted regardless of group (PD or control), the general rank order being index, middle, little, and ring finger.

Discrete time points during grasping were selected and used to evaluate, statistically, the general force sharing patterns across time (see Methods). Repeated-measures ANOVA revealed no differences among groups at any time point. There was, however, a significant effect of time for the index and little fingers. A post hoc test revealed that the percentage of index finger force was smaller during the force-rise than during the other four periods. Conversely, the percentage of little finger force was larger during the force-rise and lift than during the three hold phases. It should be noted, however, that the maximum difference across time periods in both digits was small (~5 and 3% thumb normal force, respectively). Figure 4B shows the data for all subjects (PD and age-matched control, left and right columns, respectively). It can be noticed that in general both controls and PD patients show consistent force sharing patterns from load force onset to hold, with the force amplitude rank order being maintained across the entire task.

Covariation of Normal Forces in the Time Domain

Overall, both PD and control subjects demonstrated strong covariations across digit pairs (n = 10) during the force-rise phase (0.99 ± 0.01 and 0.97 ± 0.01, respectively), with the strength of these covariations being less in the lift (0.65 ± 0.13 and 0.54 ± 0.17, respectively) and hold (0.70 ± 0.11 and 0.63 ± 0.15, respectively). The repeated-measures ANOVA found no statistical difference between groups, suggesting that both PD and controls employed a similar strategy for force development and maintenance.

Frequency Domain Analysis

One of the key questions of the present study was to assess whether the tendency for synchronization of normal forces found in two previous studies (28, 30)
would still be found in PD patients. This was especially interesting considering the existence of AT in some PD patients and the possibility that it may result in an entrainment of digit forces, i.e., phase-shifting toward or away from \( \pm 0^\circ \), due to its significant oscillatory characteristics at specific frequencies.

Fast Fourier analysis was carried out on the force produced at each digit during the hold phase. Figure 5 shows the spectral information from these calculations, i.e., bode plots of amplitude (Newtons squared) plotted against frequency (0.5 to 17 Hz) for each digit. The bode plots provide a perspective in the range of variation observed in our PD patients (\( n = 9 \)) as defined by three criteria:

1. Upper extremity score on the UPDRS (Table 1);
2. Distinctiveness in their frequency spectrum in overall amplitude and structure compared to controls;
3. Degree to which a modal frequency was present at AT frequency. We defined modal frequency as a single peak that tended to dominate the power spectrum, as determined by its overall peak amplitude, within the 0.5- to 17-Hz range across several digits.

**FIG. 4.** Emergence of force sharing pattern during grasping phases. A shows the time course of normal forces exerted by the index, middle, ring, and little fingers during the first three phases of grasping for two PD (BJ and ME, left) and two control (HM and AW, right) subjects (data are averages of 10 trials). B shows the sharing patterns of normal forces from PD (left) and control (right) subjects measured at discrete time points of grasping. The values are averages from all subjects (± standard deviations of the mean). The normal forces shown in both panels are normalized relative to the thumb normal force.
For example, RJ (PD; thick, black dashed line) shows very little variation from control subjects in the overall appearance of their frequency spectrum. Conversely, KW (PD; thick gray line) and GZ (PD; thin black line) have distinctly different bode plots than that of control subjects, especially as it relates to the predominant, modal frequencies with significant peak amplitudes observed in the 7- to 9-Hz range across all five digits. On the other hand, LC (PD; thick black line), although exhibiting a significantly lower amplitude than that of KW and GZ, still retained a fairly prominent, modal frequency at 8 Hz in Tx, Ix, and Mx. Interestingly, KW, GZ, and LC had three of the five highest UPDRS Motor Exam (Subscale III) and Upper Extremity scores.

Summarily, these bode plots illustrate several items. First, not only is there a difference in the overall amplitude of modal frequency components seen across PD patients but also the frequency with which this modal frequency occurred tended to vary slightly across PD patients (7–10 Hz). For instance, KW’s (PD) predominant tremor frequency was 7–7.5 Hz while LC’s (PD) was approximately 8.5 Hz (Tx, Ix, and Mx). Furthermore, not every PD patient (e.g., RJ) nor every digit (e.g., LC, digit Lx) showed the presence of a predominant, modal frequency and if all digits did (e.g., KW), their peak amplitudes tended to vary across digits. Therefore, due to the idiosyncratic variation in AT frequency, amplitude, and affected digit, we evaluated phase differences within subjects, comparing PD patients only to their respective controls. We want to emphasize that this grouping of subjects was done only to standardize our comparisons, as most control subjects had similar behavior responses (see bode plots, Fig. 5).

We computed phase differences between normal forces from all pairs of digits on data from individual subjects and frequency (n = 34). Across most subjects, we found that a predominant proportion of phase differences distributions was nonrandom (Rayleigh test; see Methods and Fig. 1B), with significant distributions ranging from 72.3 to 99.7% in eight of nine PD and 63.2 to 100% in eight of nine controls. One PD (JO) and one control (EB) showed lower percentages of significant distributions, i.e., 42.9 and 50.3%, respectively. These differences, compared to the other eight subjects in both groups, did not appear to be a consequence of either age or disease severity.

Figure 6 shows the phase differences for all digit pairs combined for two PD (KW and LC) and two control (HL and SB) subjects (left and right columns, respectively). Although some small idiosyncratic differences exist across frequencies, a predominant number of distributions tended to cluster at 0° in both groups. What is very interesting, however, is that in PD patients, phase differences at approximately the tremor frequency range (7–9 Hz) are not predominantly at 0°. In contrast, controls show relatively consistent, unimodal distribution around 0° across the entire frequency spectrum (0.5 to 17 Hz).

To evaluate this apparent “disruption” in the synchronization of forces more closely, we calculated the mean angle and angular deviation of phase difference distributions, plotting only the significant distributions for these values (circles and bars, respectively) at each digit pair (n = 10) and across all frequencies (n = 34) in Fig. 7. In many cases (digit pair, frequency, and experimental group), the mean angle tended to cluster at very small angular values, i.e., −0°, across the range of frequencies studied (0.5–17 Hz). However, this was not necessarily the case for frequencies at and adjacent to the predominant tremor frequency in PD patients (LC, Fig. 7, bottom left). It can be noticed that at this frequency (−8.0 Hz) either the distribution was ran-

![FIG. 5. Bode plots. Power spectral information between 0.5 and 17 Hz from the hold phase is plotted for four PD patients (RJ, GZ, LC, KW; left) and four controls (HM, BF, SB, HL; right). A fast Fourier transform was calculated for individual trials and then averaged across all 10 trials for each digit. For display purposes, the mean offset was removed and a high-pass (>2 Hz), Butterworth filter (sixth order) was carried out to improve readability.](image-url)
dom (in which case the mean angle and angular deviation are not plotted) or the significant distributions did not cluster at $-0^\circ$. Instead, the mean angles of the distributions were shifted away from $0^\circ$, often in very systematic ways (e.g., see Tx–Mx, LC). In this case, at tremor frequency (8 Hz) the distribution was not sig-

**FIG. 6.** Distributions of phase differences in normal forces exerted by digits. Phase differences between forces exerted by all digit pairs ($n = 10$) are plotted as 3-D histograms across the range of frequencies from 0.5 to 17 Hz. The data are for two PD (KW and LC, left) and two control (HL and SB, right) subjects. All trials ($n = 10$) for each digit pair are displayed. For graphical purposes, phase differences, ranging from $-180$ to $+180^\circ$, were binned into $5^\circ$ intervals.

**FIG. 7.** Mean angle of phase difference distributions, LC vs SB. The mean angles of phase difference distribution ± the angular deviation (circles and dotted line, respectively) computed on the significant phase difference distributions are shown for a PD (LC, bottom left) and control (SB, upper right) subject. Data are shown for each digit pair ($n = 10$). Only values from significant distributions are plotted. For clarity and to emphasize the area at and around tremor frequency, we have added dotted “raster” lines that highlight the $-6$-to-$12$-Hz region.
significant. At 8.5 Hz, the significant distribution was nearly out-of-phase (180°) while at 7.5 Hz the significant distribution was approximately 90° phase shifted. In addition, the angular deviation at frequencies close to that of AT were typically within a range consistent to that seen at all other frequencies in the spectrum, implying that these phase-shifted and out-of-phase patterns were consistently produced.

It should be noted that although this phenomenon was seen across most subjects with obvious AT (e.g., KW, LC, GZ, and HW), the extent to which these disruptions occurred was definitely idiosyncratic to each subject. Figure 8 shows another comparison in mean angle and angular deviation between a PD (GZ; Fig. 8, bottom left) and control (BF; Fig. 8, upper right). Although a shift in the mean angle clearly occurs within particular frequencies (at and around tremor, 7 Hz) and at certain digit pairs (Tx–Rx, Mx–Lx) for GZ, it is much less pronounced than that observed for LC (Fig. 7).

The composite of these findings suggests that predominant AT, as exhibited in normal force production at the digits in some PD patients, disrupts the synchronization of forces typically observed among digit pairs during multifingered grasping (28, 30). This disruption typically occurs at and around the tremor frequency. However, across many other frequencies, synchronization patterns at ~0° are generally preserved. This disruption is not ubiquitous across digit pairs (e.g., Fig. 7, Tx–Ix and Mx–Rx; LC) and is idiosyncratic to subject (Figs. 7 and 8). Furthermore, it should be noted that a lack in synchronization is also observed in digit pairs where only one finger has a prominent tremor (e.g., Figs. 5 and 7, Ix–Lx, LC).

Coherence Analysis

It should be noted that even though a similar predominant frequency, i.e., a modal component dominating the spectrum, may be apparent in two digits (see Fig. 5, bode plots) this does not necessarily imply that these two digits will be correlated at this frequency (e.g., Ix–Rx in LC or Mx–Lx in KW, Fig. 9). Therefore, only by looking at coherence analysis, which determines at which frequencies digit normal forces are least correlated, in conjunction with the phase difference distributions (Figs. 7, 8, and 9, respectively) can we begin to answer more definitely whether AT influences force synchronization patterns between digits.

Figure 9 shows coherence values (±SD) for three subjects, one control (EB) and two PD patients (LC and KW), at three representative digit pairs (Tx–Ix, Ix–Rx, Mx–Lx). Interestingly, we discovered that in all those subjects with a predominant, modal AT (LC, KW, HW, GZ) there was a systematic decrease in the coherence within specific digit pairs at AT frequency, compared to the entire complement of frequencies (0.5–17 Hz). In contrast, in control subjects (Fig. 9, EB), as well as those PD patients with no distinct AT, fluctuations in
The coherence and the degree of intertrial variability were more uniformly distributed across the entire frequency range.

Specifically, in I-R (LC, Fig. 9) there was a predominant drop in coherence at approximately 7–8 Hz, the exact region where a modal frequency in the index finger bode plots (LC, Fig. 5), as well as a disruption in the mean angle of phase differences (LC, Fig. 7), were observed. Conversely, in T-I there was very little change in coherence at this frequency. Similarly, there was little disruption observed in the mean angles, despite the fact that this particular frequency contained a large proportion of the total power in both the thumb and the index fingers (LC, Fig. 5). As can be noticed from Fig. 9, this lack of coherence around AT frequency was idiosyncratic to subject and digit pair specifics. For example, KW shows no change in coherence around their AT frequency in digit pair, Mx-Lx, while LC does. Furthermore, KW has a distinct drop in coherence at Ix-Rx but not at the other two digit-pairs, Tx-Ix or Mx-Lx.

In general, the systematic drop in coherence was not observed in any control (Fig. 9, EB) or in those PD patients exhibiting lower motor exam scores and non-distinct AT. Our findings also suggest that AT does not influence the relationship between all 10 digit pairs, i.e., force-coupling at particular frequencies, in a ubiquitous fashion during a five-digit grasping task.

**DISCUSSION**

The primary objective of this study was to determine the extent to which PD influences the coordination and control of grip forces in five-digit grasping. Our specific aims were to examine whether PD patients could accurately and systematically scale grip forces across five-digits, as has previously been described in neurological normal individuals (28–30). In addition, we wanted to determine whether PD patients would retain a strong, in-phase, synchronization pattern at all five-digits across a large span of the functional force range (0.5–17 Hz).

We found that the global features observed in five-digit grasping, i.e., overall amplitude of normal force, force sharing pattern, and covariation of force at the digits, are strikingly similar between PD patients and controls. Force rate profiles were found to be essentially bell-shaped across PD patients and controls. Nevertheless, step-like force rate profiles were found in PD patients, but only in those patients exhibiting AT (Fig. 3). Furthermore, subtler aspects of the coordina-
tion between digits, as seen in the frequency domain, are not necessarily preserved in PD patients. Specifically, we found a decoupling of normal forces at and around action tremor frequency, as revealed by the randomness of their relationships and the lesser extent of their synchronization. These findings are discussed in relation to the neural mechanisms that might underlie physiological synchronization of forces and its pathological disruption.

Grip Force Amplitudes and Force Sharing Patterns

In agreement with the results on two-digit grasp by Ingarsson and colleagues (20)—and in disagreement with Muller and Abbs (25) and Fellows et al. (13)—PD patients in our study produced grip force amplitudes similar to controls. Most importantly, they systematically parceled forces among the four fingers opposite the thumb, with the general rank order being index, middle, little, and ring finger. In fact, this force-sharing pattern emerged very early in the grasp-to-lift sequence, i.e., during the force-rise phase, in both PD and controls and remained relatively unchanged for the remainder of the lift and hold. In PD patients, this pattern did not show any delay in emerging, in general, nor did it demonstrate significant fluctuations when transitioning from one grasping phase to another, e.g., going from the force-rise to lift phase, as might be anticipated from previous two-digit grasping (20) and other movement sequencing research (27).

Surprisingly, this force-sharing pattern in PD patients did not exhibit significant within- or across-trial variability compared with controls. Unfortunately, it is difficult to make a direct comparison between our study (done with five-digit grasping) and others examining force variability across different tasks, such as orofacial movement (1) or force tracking (31). Nonetheless, our findings are generally in contrast to this literature, which reports that PD patients tend to exhibit increased variability in force control. The fact that PD patients in our study did produce forces within each digit in a consistent fashion and comparable to controls suggests that whole-hand grasping is a well-learned skill and therefore characterized by limited variability.

In general, these findings, in conjunction with the two-digit work of Gordon and colleagues (18), suggest that PD patients can accurately preprogram grip forces across all five digits during grasping. They can also achieve this pattern in a relatively stable and systematic manner both within and across trials, suggesting that tactile and haptic sensory systems are intact and well integrated with motor output. Last, these findings imply that the force-sharing patterns observed in several recent studies (28–30) are robust and preserved even in PD patients. Furthermore, even when taking into consideration age (~55–83 years; both groups) and PD severity (UPDRS Motor Exam, Subscale III; 26–38), it would appear that force-sharing patterns are not influenced by either of these factors.

Force Synchronization Patterns

Two previous studies (28, 30) have shown that fingers tend to exert force in a synchronous fashion during five-digit grasping. Remarkably, this force coordination pattern appears to be robust, as it is consistently found regardless of object center of mass location (30) as well as predictability of center of mass location and handedness (28). Nonetheless, our present data indicate that these force synchronization patterns are not as consistent in the presence of action tremor.

A disruption in the force synchronization patterns tended to occur primarily at and/or around the action tremor modal frequency, resulting in either (a) a shift of phase differences away from ~0° (in-phase) (Figs. 7 and 8) or (b) large intertrial variability of phase differences, i.e., random phase difference distributions (Figs. 1B and 6). This disruption was evident within specific digit pairs in those PD patients most affected by action tremor and either absent or nonsystematic in PD patients with mild or nondistinct action tremor and in controls. These findings imply that disruptions in force synchronization are action tremor specific, rather than PD specific.

Clinical Implications

Does a lack in force synchronization at the digits contribute to the lack of manual dexterity often observed in PD patients? Based on the evidence reported here we do not believe so. The disruption in between-digit force synchronization due to AT is very specific and focal, while grip forces across a majority of frequencies remain synchronized. This lack of synchronization also appears to affect some but not all digit pairs. Most importantly, PD patients seem to make no quantifiable attempt to compensate for the lack of force synchronization at AT frequency, e.g., by increasing total force output, as a means to ensure that they lift and hold the object vertically and prevent it from tilting and/or slipping. Therefore, we conclude that a small, local disruption in force coupling at the digits has a relatively small impact on the overall grasp and lift action in PD patients.

Action Tremor and Control of Muscle Activity in Parkinson’s Disease

We should stress that the present study was designed to investigate primarily the coordination of fingertip forces. Nevertheless, some of our results prompt us to speculate beyond our measured variables to account for what we consider the most interesting result, i.e., the selectivity of the disruption of force relationship...
at approximately action tremor frequency. In fact, this feature might provide some clues as to the neural mechanisms that are responsible for the force synchronization patterns as well as its interaction with the mechanism responsible for action tremor.

Studies of muscle activity in PD patients with action tremor during isometric force production tasks have revealed abnormal MU properties. Milner-Brown and colleagues (24) reported (a) variable delays in MU at low force levels; (b) upon recruitment some MUs stopped firing or fired intermittently; (c) some MUs fired at abnormally low frequencies (see also (7)). Other features of force control in PD patients with action tremor are irregular fluctuations in MU firing frequencies (10) and the presence of short interspike intervals that are strongly correlated with tremor amplitude (7, 11). As shown by electrical stimulation of the radial nerve, MU firing at longer interspike intervals causes reduction in torque amplitude and tremor in the torque profile (5). Furthermore, analysis of MU synchronization (10) revealed that MU cross-correlograms from PD patients—with either action or essential tremor—were characterized by distinct profiles, i.e., weaker synchronization strength and broader base of the peak than in control subjects. It should be noted that the aforementioned studies focused on correlating MU behavior and force at one digit. Yet, a research question that has not been addressed in the literature regards the extent to which abnormal MU properties in muscles serving individual digits might affect the coordination between digits in a task such as ours, i.e., multifingered grasping.

It is difficult to infer a causal relationship between a dysfunctional neural drive to each digit and the altered coordination of multiple grip forces described here. Nevertheless, our data do provide some insight into tremor-specific impairments on the control of five-digit grasping. Phase difference and coherence analyses revealed that the mechanism underlying action tremor interferes with the mechanism responsible for force synchronization. This was evident in the weakening of the force relationship between digits at this specific frequency. Interestingly, across many other frequencies little or no influence of action tremor was observed.

It has been suggested (28, 30) that force synchronization patterns observed across digit pairs might be accounted for by a common drive (9) to muscles innervating each of the finger and the thumb, thus leading to in-phase fluctuations, i.e., a constrained timing, of forces exerted by all digits. Within this scenario, it would appear that the above abnormalities in MU behavior associated with action tremor might result in weaker or no between-digit force synchronization at action tremor frequencies, whereas the common drive appears to be unaffected at many neighboring frequencies.

Further work, especially the recording of single motor units during five-digit grasp (currently underway in our laboratory), is necessary in order to provide support for these claims. Yet, based on the current understanding of force synchronization at the digits and its interaction with action tremor, the logic presented here provides a conceptual framework for formulating future investigations on multidigit control of grasping.

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REFERENCES


