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Coordination deficits during trunk-assisted reach-to-grasp movements in Parkinson's disease

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Abstract

The present study investigated how Parkinson's disease (PD) affects temporal coordination among the trunk, arm, and fingers during trunk-assisted reach-to-grasp movements. Seated participants with PD and healthy controls made prehensile movements. During the reach to the object, the involvement of the trunk was altered based on the instruction; the trunk was not involved, moved forward (flexion), or moved backward (extension) in the sagittal plane. Each of the trunk movements was combined with an extension or flexion motion of the arm during the reach. For the transport component, the individuals with PD substantially delayed the onset of trunk motion relative to that of arm motion in conditions where the trunk was moved in the direction opposite from the arm reaching toward the object. At the same time, variability of intervals between the onsets and intervals between the velocity peaks of the trunk and wrist movements was increased. The magnitudes of the variability measures were significantly correlated with the severity of PD. Regarding the grasp component, the individuals with PD delayed the onset of finger movements during reaching. These results imply that PD impairs temporal coordination between the axial and distal body segments during goal-directed skilled actions. When there is a directional discrepancy between the trunk and wrist motions, individuals with PD appear to prioritize wrist motion that is tied to the task goal over the trunk motion. An increase in disease severity magnifies the coordination deficits.

Keywords

Prehension; Kinematics; Coordination; Finger; Trunk

Introduction

A loss of striatal dopamine, one of the main pathological changes in individuals with Parkinson's disease (PD), affects the function both in the basal ganglia and in related areas in the thalamus and cortex (DeLong and Wichmann 2007; Fogelson et al. 2006; Galvan and Wichmann 2008). Basal ganglia dysfunction causes deficits in the temporal and/or spatial coordination of effector components in multi-segment movements. It is known that individuals with PD show impairments in finger–wrist coordination (Benecke et al. 1986; Teulings et al. 1997), elbow–shoulder coordination (Alberts et al. 2000; Fradet et al. 2009; Seidler et al. 2001), and arm–hand and arm–trunk coordination (Bertram et al. 2005; Castiello et al. 1993; Rand et al. 2010; Wang et al. 2006) during various limb movements.

Reach-to-grasp movement, which is one of the most essential motor behaviors in our daily life, consists of an arm transport component and a grasp component. Since this behavior is well-trained through daily life, the two components show stereotypic kinematic features in healthy individuals (e.g., Jeannerod 1981, 1984; Rand et al. 2000). Despite a recent view that reach-to-grasp actions emerge following the minimization of the difference between the actual body configuration and its referent prototype specified by the brain (Pilon et al. 2007; Yang and Feldman 2010), the predominant notion still adheres to the traditional view that independent cerebral cortical areas are involved in the regulation of each of the prehensile action components, i.e., the arm transport and the grasp (Baumann et al. 2009; Binkofski et al. 1998; Clower et al. 2005; Connolly et al. 2003; Matelli and Luppino 2001; Ménoret et al. 2013; Riehle et al. 2013). The basal ganglia are known to project to these areas via the thalamus (Clower et al. 2005; Rizzolatti et al. 1988). Thus, the basal ganglia are well suited to play a role in controlling multi-segment/component actions, such as prehensile actions. Indeed, hypometric grip aperture and discoordination between the transport and aperture components have been reported in PD (e.g., Castiello et al. 1993; Jackson et al. 2000; Schettino et al. 2006).

The involvement of the trunk during prehension expands the reach distance beyond the length of the arm for grasping an object (Kaminski et al. 1995), enabling us to make a wide variety of prehensile movements. For a target object located within the arm's reach, the trunk usually serves to stabilize the body posture for arm reaching (Kaminski et al. 1995). However, it cannot be used as a stabilizer for the arm motion when the trunk is actively moved during prehensile movements. Instead, it increases the complexity of movements, which is defined by the number of components or parts involved in the motor skill (Magill 2010). Thus, the need to involve the trunk in a reach-to-grasp movement results in a more complex action than a reach-to-grasp movement in which the trunk does not need to be involved.

It is known that, during trunk-assisted reach-to-grasp movements, the arm is functionally coordinated with the trunk to make a smooth endpoint trajectory of the arm reaching toward a target object (Marteniuk and Bertram 2001; Saling et al. 1996; Wang and Stelmach 2001). Trunk motion is usually initiated prior to arm motion (Rand et al. 2012; Saling et al. 1996; Wang and Stelmach 2001). However, it is well integrated into arm reaching by the time of peak wrist velocity, thereby preparing for subsequent integration with the grasping component (Rand et al. 2012; Yang and Feldman 2010).

Previous studies on trunk-assisted reach or reach-to-grasp movements showed that individuals with PD have larger mean time intervals between onsets or offsets of the arm and trunk motions compared to healthy controls (Poizner et al. 2000; Tunik et al. 2004; Wang et al. 2006). Wang et al. (2006) further demonstrated that the interval between the finger-aperture onset and trunk-motion onset was prolonged in individuals with PD,

especially when a prehensile task required an unnatural sequencing between the trunk and arm within the transport component. This suggests that PD affects the temporal coordination among various segments when a behavioral context goes beyond a familiar domain. These observations together indicate an impaired temporal coordination between the arm, trunk, and finger movements, which includes a failure to initiate various movements in a timely fashion (Brown and Mars-den 1991; Heilman and Valenstein 2012). Such failure may reflect a deficient gating mechanism by the basal ganglia, which affects the cortical functions of action selection and implementation (Hikosaka et al. 2000; Smith et al. 2011; Terao et al. 2011; Ueda and Kimura 2003).

The aforementioned study by Wang et al. (2006) only examined the most common combination of trunk and arm movements (trunk flexion and arm extension) for trunk-assisted prehension in individuals with PD. However, previous studies in healthy adults have examined different combinations of motion directions between the trunk and arm during reaching (Ma and Feldman 1995; Pigeon et al. 2000) and reach-to-grasping (Rand et al. 2012). The latter study demonstrated that trunk extension was less integrated into the control of wrist transport than trunk flexion. The likely reason is that the trunk extension is less frequently used in daily life than the trunk flexion in prehensile actions, resulting in less optimized coordination between the axial and distal segment. It still remains unclear, however, how PD affects the control of trunk-assisted prehension when such an unfamiliar coordination pattern is required.

Recent studies suggest that motor impairments of individuals with PD are associated with a greater involvement of the goal-directed control than the habitual control as compared to healthy adults (Redgrave et al. 2010; Torres et al. 2011). The habitual control, which is established through considerable experience/training, is generally fast and imposes low neural computational demands (Hikosaka et al. 1999; Redgrave et al. 2010; Schneider and Chein 2003). Conversely, the goal-directed control, which is cognitively controlled, thus a non-habitual control process, is slow and imposes high computational demands. The dorsolateral and the dorsomedial striatum in the basal ganglia, each of which connects functionally different cerebral cortical areas, are thought to regulate habitual and goal-directed control, respectively (Redgrave et al. 2010; Miyachi et al. 1997). Thus, coordination involving less familiar trunk motion (extension) during prehensile actions likely imposes higher processing demands on the goal-directed control in individuals with PD and that likely induces greater coordination impairments.

The aim of the present study was to further investigate temporal coordination among different body segments (finger, arm, and trunk) during trunk-assisted reach-to-grasp movements in individuals with PD. We systematically tested various combinations of trunk- and arm-motion direction. A trunk backward (extension) or forward (flexion) motion was combined with an arm extension or flexion motion. Based on the aforementioned reasons, it was hypothesized that individuals with PD would display more coordination deficits among body segments when the trunk is actively extended during reach-to-grasp movements compared to when it is flexed. For the same reasons, it was further hypothesized that the deficit in temporal coordination among body segments would increase as the severity of PD increases.

Materials and methods

Participants

Sixteen participants with Parkinson's disease (72.2 ± 7.1 [mean $\pm$ SD] years old; 10 males and 6 females) and sixteen elderly controls (71.4 ± 5.7 years old; 10 males and 6 females) participated in the study. One PD patient was excluded because not all data were recorded

due to technical difficulties. The remaining fifteen PD patients (see Table 1) did not significantly differ in age from the control group [$t(29) = 0.41, p > 0.05$]. A summary of characteristics for the participants with PD is presented in Table 1. All participants with PD were diagnosed with idiopathic PD by a neurologist in the metropolitan Phoenix area. All participants were screened using a health questionnaire and the Mini-Mental State Exam (MMSE, Folstein et al. 1975). MMSE was used to assess general cognitive function. Exclusion criteria for all participants were (1) having impairments of cognitive function (i.e., MMSE less than 26), (2) having arthritis affecting task performance, and (3) having orthopedic or visual problems that would interfere with task procedures. The inclusion criteria for participants with PD included (1) being capable of giving informed consent, and (2) having a diagnosis of idiopathic PD by a neurologist. The exclusion criteria for participants with PD included (1) having undergone any neurosurgical procedure for PD or for any other reason (e.g., stereotaxic surgery, deep brain stimulation), (2) the presence of dyskinesias, and (3) having any known neurological pathology other than PD. Inclusion criteria for control participants included (1) being capable of giving informed consent, and (2) not having known neurological impairments. The participants with PD were asked not to alter their normal medication regime on the day when they were tested. The PD medication is known to possibly improve speed and maybe even some coordinative aspects of skilled arm movements (Levy-Tzedek et al. 2011; Schettino et al. 2006; Tunik et al. 2007). This study was approved by Arizona State University's Institutional Review Board overseeing the use of human subjects in research. All subjects provided written informed consent prior to participation.

Procedures

The experimental setting and procedure were the same as the previous study conducted with healthy young adults (Rand et al. 2012). Participants were comfortably seated at a table. The distance from the participants' midline in the front and the edge of the table was adjusted for each participant so that they could move the trunk comfortably back and forth in the sagittal plane, while still being able to easily grasp an object for all conditions. The average value of this distance across participants did not significantly differ between the PD (11.4 ± 2.2 cm [mean $\pm$ SD]) and control groups (10.2 ± 3.0 cm; $t(29) = 1.30, p > 0.05$). The maximum reach distance without bending the trunk forward was measured between the tip of the index finger and the edge of the table. The average maximum reach distance across participants was 51.2 ± 4.7 and 48.4 ± 3.2 cm for the PD and control groups, respectively. There were two target locations, one at 5 cm (T1) and one at 25 cm (T2) from the edge of the table. Depending on the condition, one location was used as the start position, while the other was used as the target position (Fig. 1). T1 served as the start position and T2 served as the target location for conditions related to arm-extension movement. Conversely, T2 served as the start position and T1 served as the target location for conditions related to arm-flexion movement. A cylindrical target object (height 2.5 cm, diameter 3 cm) was placed on the target location for prehensile movements.

At the beginning of each trial, participants sat with their trunk in an upright position without using the back of the seat. Participants kept their thumb and index finger together, placed the ulnar side of the hand on the table, and rested their index finger and thumb at the start position. Subsequently, the examiner said "ready." Then, after a random delay (between 1 and 2 s), an auditory "go" signal was delivered. In response, the participants reached for the object, grasped it with the thumb and index finger, and lifted it a few centimeters off the table. The completion of the lift was the end of a trial. The participants then put the object down on the table, brought their trunk back to an upright position, and placed their hand at the starting position for the next trial. The participants were instructed to move at a fast but comfortable speed. If trunk involvement was required to reach for and grasp the cylinder,

participants were instructed not to rotate their trunk, but to move their whole trunk forward or backward while reaching for the object. If trunk involvement was not necessary, participants were instructed not to move the trunk.

To examine the effects of the arm and trunk motions on the control of reach-to-grasp movements, four conditions with different arm and trunk combinations were tested: (1) trunk extension, arm extension, (2) trunk extension, arm flexion, (3) trunk flexion, arm extension, and (4) trunk flexion, arm flexion (Fig. 1). Additionally, there were two conditions in which the reach-to-grasp movements did not require trunk movement (no trunk), each of which was combined with the two different arm motions (arm extension and arm flexion). All four trunk-involved conditions and the two no-trunk conditions were randomized and counterbalanced across participants to reduce practice and fatigue effects. Prior to the recording of each condition, participants practiced a few trials to familiarize themselves with the required movements. A block of twelve trials was performed for each condition, in which the last ten trials were used for data analysis. Thus, sixty trials were analyzed for each participant.

Trunk, wrist, and finger positions during reach-to-grasp movements were recorded using an Optotrak 3D system (Northern Digital). Infrared light emitting diodes (IREDs) were placed on the tips of the thumb and index finger, the wrist, the elbow, the shoulder, and the middle of sternum. An additional IRED was placed on the cylinder in order to record its position and movement. Positions of the IREDs were sampled at a rate of 100 Hz.

Data analysis

Kinematic characteristics related to the grip and the transport components were analyzed in 3D. The transport component was assessed based on the position of the wrist IRED. Furthermore, the movement of the trunk was assessed based on the position of the trunk IRED placed on the sternum. Wrist (trunk) velocity during the reach was tangential velocity calculated as the first derivative of wrist (trunk) position. Derivatives were calculated using the sliding window technique, where the data points within the window (the window width was 7 points) were approximated with a quadratic polynomial (Rand et al. 2006, 2010, 2012). The polynomial was then used for calculating the analytic derivative at the window's center (or at other points when the window overlapped the beginning or end of the data array representing the curve). Thus, calculating derivatives using this method also provided data filtering. The grasp component was assessed based on the positions of the IREDs on the index and thumb fingertips. Grip aperture was defined as the resultant distance between these two IREDs. The end of grasp was identified as the time when both fingers came into contact with the object. The end of the transport was defined as simultaneous to the end of grasp. Calculation of the onset of transport and aperture was performed by an automated movement parsing algorithm (Teasdale et al. 1993; algorithm B). In some trials, participants initiated the trunk motion in the direction opposite from the prescribed movement direction and later changed it to the prescribed direction. In such case, the onset of trunk motion was determined as the time at which the trunk motion was initiated in the prescribed direction. The incidence of such a behavioral pattern was counted for each participant separately in the trunk-extension, arm-extension condition and the trunk-flexion, arm-flexion condition. The group difference of the number of incidence was assessed using a Mann–Whitney U test for each condition.

Basic kinematic parameters related to the transport component included (1) transport time (from wrist onset to the end of grasp), (2) the time to peak wrist velocity, (3) peak wrist velocity, (4) peak trunk velocity, (5) the duration from trunk onset to wrist onset, and (6) the duration from peak wrist velocity to peak trunk velocity. Parameters related to the grip aperture component included (7) peak grip aperture, (8) the time to grip aperture onset (from

wrist onset to grip aperture onset), (9) the time to peak grip aperture (from wrist onset to peak grip aperture), (10) the time from peak wrist velocity to the time of peak grip aperture, and (11) the hand-to-target distance at grasp initiation (i.e., the distance that the hand traveled from peak aperture to the end of grasp). The hand-to-target distance was calculated as a vector length between two positions of the wrist IRED. The above parameters of (2), (5), (6), (8), (9), and (10) were expressed as percentages of transport time.

A mean value across all trials for each participant was calculated for each condition. For the above parameters of (5), (6), (8), (9), and (10), SD across all trials within each participant and each condition was also calculated as a variability measure of temporal coordination. These mean values and SD values were used for statistical comparisons using a mixed model ANOVA with group as a between-subjects factor and trunk motion and arm motion as within-subject factors for the parameters that were included in the no-trunk conditions. Namely, a 2 (group) $\times$ 3 (trunk motion: no trunk, extension, flexion) $\times$ 2 (arm motion: extension, flexion) mixed model ANOVA was used. For the parameters that were not included in the no-trunk conditions, a 2 (group) $\times$ 2 (trunk motion: extension, flexion) $\times$ 2 (arm motion: extension, flexion) mixed model ANOVA was used with trunk motion and arm motion as repeated measure factors. When appropriate, post hoc comparisons were performed using Bonferroni corrected t-tests ($\alpha = 0.05$) in order to identify significant differences between individual cell means. To focus data presentation on PD-related behavioral changes, text includes only condition main effects, group effects, and interaction effects involving the group factor. Mauchly's test was used to determine whether sphericity could be assumed. Huynh-Feldt epsilon was reported for the results of ANOVA only when Mauchly's test was found significant.

Results

Kinematic characteristics of the transport component

The effects of different arm- and trunk-motion directions on the transport component are summarized in Table 2. Across the groups, wrist transport time was significantly increased ($p < 0.001$) and peak wrist velocity was decreased ($p < 0.001$, Fig. 2a) when movement of the trunk contributed to the reach compared to when it did not contribute (see the inferential statistics in Table 2). The peak wrist velocity was substantially decreased when a trunk flexion was combined with an arm flexion, and the interaction effect of trunk motion by arm motion was significant ($p < 0.05$). In contrast to the arm movement, the speed of trunk movement was stable across experimental conditions.

The PD group produced significantly slower wrist transport time ($p < 0.01$) and lower peak wrist velocity ($p < 0.01$) and peak trunk velocity ($p < 0.01$) than the control group. The PD group increased the peak wrist velocity less than the control group when movement of the trunk did not contribute to the reach, resulting in a significant interaction of group by trunk motion (Fig. 2a, $p < 0.05$).

Temporal coordination between wrist and trunk movements—To determine whether the participants initiated the wrist movement at a consistent time after the onset of trunk movement, the time required from the trunk onset to wrist onset was measured and expressed as the percentage of reach duration. The trunk motion started either earlier or later than that of the wrist motion depending on the experimental conditions (Fig. 3a, Table 2). The onset timing of the trunk motion did not show a significant group effect. However, this timing was flexibly altered depending on the combination of movement directions among the body segments as well as among groups, and hence, there was a significant 3-way interaction of group by trunk motion by arm motion ($p < 0.05$). The PD group made substantial delays in the onset of trunk motion for the conditions where the trunk moved in

the direction opposite from the arm reaching direction (i.e., the trunk-flexion, arm-flexion condition and the trunk-extension, arm-extension condition, Fig. 3a). Under these conditions, the participants with PD delayed initiation of the trunk motion, but also sometimes started the trunk motion together with the wrist motion in the same direction as the arm reaching direction. Subsequently, they changed the trunk motion to the instructed direction. As a result, the onset of trunk motion in the instructed direction might have been delayed, contributing to the observed 3-way interaction.

The above behavioral pattern (in which participants started the trunk motion in the same direction as the wrist and later changed to the instructed direction) emerged on average 24.7 ± 8.8 [SE] % of the trials in the trunk-flexion, arm-flexion condition in the PD group. Conversely, it occurred in 1.3 ± 1.3 % of the trials in the control group. The group difference was significant ($N = 31$, $U = 192.50$, $p < 0.01$). Two-thirds of the PD participants produced this behavioral pattern at least once. In the trunk-extension, arm-extension condition, however, the incidence of this pattern averaged 7.3 ± 5.4 % of the trials in the PD group, and it was not found (0 %) in the control group. The group difference was not significant ($N = 31$, $U = 144.00$, $p > 0.05$). One-fifth of the PD participants produced this pattern at least once. Thus, this behavior was mainly observed in the trunk-flexion, arm-flexion condition.

Additionally, to examine the influence of the aforementioned behavioral pattern (in which participants started the trunk motion in the same direction as the wrist and later changed to the instructed direction) on the observed onset delay of trunk motion in the PD group, further analysis was done of data from PD participants who had trials with and without an initial wrong direction of the trunk. We made a set of trials with movement of the trunk only in the correct direction (partial-set) and compared it to the set of all trials (all-set; i.e., the full dataset including trials in which the trunk initially moved in the wrong direction and trials in which the trunk moved in the correct direction from the start) by using a paired t test in both conditions (i.e., trunk-extension, arm-extension and trunk-flexion, arm-flexion) separately. The mean trunk onset timing did not significantly differ between the two datasets in either the trunk-extension, arm-extension condition (partial-set: -5.7 ± 3.5 [SE] %; all-set: -10.6 ± 5.7 %, $t(14) = 1.08$, $p > 0.05$) or the trunk-flexion, arm-flexion condition (partial-set: -1.6 ± 4.5 %; all-set: -5.9 ± 5.7 %, $t(12) = 2.16$, $p > 0.05$). Thus, an inclusion or exclusion of above behavioral pattern into the calculation of trunk onset timing did not significantly alter the results of the PD group.¹

In terms of the temporal coordination between the peaks of the trunk and arm velocities during the wrist transport to the object, the trunk velocity reached its peak later than that of the wrist velocity. The time from the peak wrist velocity to the time of peak trunk velocity was also expressed as a percentage of reach duration (Table 2, Fig. 3b). The values of this time measurement across the conditions had substantially larger range for the PD group than the control group. This parameter was heavily influenced by the aforementioned delay of trunk movement onset in the trunk-flexion, arm-flexion condition and the trunk-extension, arm-extension condition for the PD group, and hence, it was substantially prolonged under these conditions. This resulted in the 3-way interaction of trunk motion, arm motion, and group ($p < 0.05$).

¹We are interested in the neural control of the movement in the correct direction because the current task was to perform specific combinations of motion directions between the trunk and arm based on instructions. If individuals initially move in the wrong direction, they have to reprocess their movement, and the time spent for moving in the wrong direction is possibly used to plan and prepare the movement in the correct direction. For this reason, the current study focuses on analyzing the onset time of the trunk movement in the correct (instructed) direction.

Temporal variability between wrist and trunk movements and its relation to disease severity

—To further determine whether the temporal relationship between the onsets of trunk and arm movements was consistent across trials within each condition, the standard deviation (SD) of this duration across trials was calculated as a variability measure of temporal coordination (Fig. 3c). This parameter was expressed as the percentage of reach duration. The PD group had a significantly greater variability of trunk onset timing than the control group ($F(1,29) = 9.40$; $p < 0.01$; $\eta_p^2 = 0.25$). The increased variability for the PD group was again observed in the conditions where the trunk motion direction was opposite to the arm reaching direction (i.e., the trunk-flexion, arm-flexion condition and the trunk-extension, arm-extension condition). As a result, the 3-way interaction of trunk motion, arm motion, and group was significant ($F(1,29) = 6.54$; $p < 0.05$; $\eta_p^2 = 0.18$).

Furthermore, the variability across trials was also measured for the time from the peak wrist velocity to peak trunk velocity and expressed as the percentage of reach duration (Fig. 3d). The PD group had a greater variability than the control group ($F(1,29) = 5.89$, $p < 0.05$; $\eta_p^2 = 0.17$). The pattern of changes in this variability measure among different conditions was similar to that of trunk onset timing (Fig. 3c), except the trunk-extension, arm-extension condition. Under this condition, the control group showed greatest variability, whereas the PD group produced a variability level similar to that of the control group (Fig. 3d). As a result, there were significant interaction effects between trunk motion and group ($F(1,29) = 5.80$, $p < 0.05$; $\eta_p^2 = 0.17$) and arm motion and group ($F(1,29) = 6.15$, $p < 0.05$; $\eta_p^2 = 0.18$).

In addition, there is a possibility that greater variability observed in the PD group (Fig. 3c, d) is caused by the slowness of their movements. To test this possibility, we first calculated the mean transport time across the four conditions involving trunk movements for each participant. Based on these mean values, the overlapping range of transport time between the two groups was identified (632–1,162 ms). Transport times of 14 controls and 7 PD participants fell in this range. When these two parameters were calculated only for these subsets of participants, the results of temporal variability showed a similar pattern, as is shown in Fig. 3c and d. Furthermore, the ANOVA revealed the same significant main effects (both group effects and interaction effects) as reported above. Therefore, the large variability found in the PD group cannot be explained solely by the slowness of their movements.

Next, we investigated the relationship between the severity of PD and the increased variability in the temporal coordination between trunk and arm movements. Correlations between the motor examination subscale of the Unified Parkinson's Disease Rating Scale (UPDRS-III) and the above variability (SD) parameters were calculated. Figure 4 shows an example of the correlation between the UPDRS-III and the variability (SD) of the duration from peak wrist velocity to peak trunk velocity in the trunk-flexion, arm-flexion condition. There was a significant correlation between variability and disease severity ($r = 0.733$, $p < 0.01$).

Table 3 summarizes the correlation coefficients between UPDRS-III and variability (SD) calculated in each condition for each of the two coordination parameters (i.e., SD of the duration between the time of trunk onset and wrist onset, and SD of the duration of the period between time of peak wrist velocity and time of peak trunk velocity). The variability of both parameters showed either significant or marginally significant correlations with the UPDRS-III for the conditions where the direction of trunk motion was opposite of the arm reaching movements (i.e., the trunk-flexion, arm-flexion condition and the trunk-extension, arm-extension condition). Thus, under those conditions, the temporal coordination between

the trunk and arm movements during reaching to the target became more variable when the severity of the disease increased.

Kinematic characteristics of the grasp component

The effects of changing arm- and trunk-motion directions on the grasp component are summarized in Table 4 (see also this table for the inferential statistics). Even though the PD group generally made smaller amplitudes of maximum grip aperture than the control group (Fig. 2b), the group difference was not significant. Across the two groups, peak grip aperture of the arm-flexion condition was significantly greater than that of the arm-extension condition ($p < 0.001$). The PD group only slightly altered the amplitude of maximum grip aperture in response to the trunk manipulation (Fig. 2b), whereas the control group produced the largest amplitude when the trunk was extended. Thus, the trunk main effect ($p < 0.01$) and the interaction of trunk motion by group showed significance ($p < 0.05$).

The location of the hand relative to the target object at the time of maximum aperture (hand-target distance for aperture closure initiation) was significantly increased when the trunk was extended compared to when it was flexed ($p < 0.05$). This distance tended to increase when the arm was extended during the reach compared to the condition where the arm was flexed ($p = 0.051$). The PD group generally produced shorter distances as compared to the control group. However, the group difference was not significant ($p > 0.05$).

Temporal coordination between the transport and grasp components and its variability—To examine whether the onset or peak timing of finger aperture was consistent relative to those of wrist transport, three temporal parameters were measured. We first examined whether the time required for initiating finger movements during reaching was altered by the direction of trunk motion and arm motion. The percentage of reach time before the onset of a change in grip aperture (grip aperture onset) was measured (Table 4). The PD group significantly delayed the onset as compared to the control group ($p < 0.05$). Next, the time from the reaching onset to peak grip aperture and the time from peak wrist velocity to the time of peak grip aperture were examined and expressed as a percentage of reach duration (Table 4). These durations were significantly altered by the trunk motion manipulation ($p < 0.05$). However, no group differences were found for both parameters.

To further assess the variability of the above three parameters of temporal coordination, SD across trials was calculated for each parameter and expressed as the percentage of reach duration. The variability of grip aperture onset was significantly greater for the PD group (the average SD across all conditions and participants: 8.7 ± 1.0 [SE] %) than that for the control group (5.5 ± 0.5 %, $F(1,29) = 9.60$, $p < 0.01$; $\eta_p^2 = 0.25$). No other effect was found to be significant.

Regarding the variability related to the timing of maximum grip aperture, the average SD value ranged from 5.4 to 7.6 % across conditions and groups for the time to peak grip aperture and ranged from 5.1 to 8.1 % for the time from the peak wrist velocity to peak grip aperture. None of these variability measures proved to be significantly different between groups, and none showed significant interaction effects between group and trunk motion or arm motion.

Discussion

The current experiment investigated temporal coordination among various body segments (finger, arm, and trunk) during trunk-assisted reach-to-grasp movements in individuals with PD. It was hypothesized that they would show more pronounced coordination deficits when

a prehensile action was combined with a trunk extension motion as compared to a trunk flexion. However, the results showed that, regardless of the trunk motion direction, temporal discoordination is most pronounced when the prehensile action requires a combination of movements in which the trunk and arm move in opposite directions. Under such combinations, the individuals with PD delayed the onset of trunk motion and produced a large variability between the onsets or velocity peaks of the arm and trunk motions. They also delayed the onset of grip aperture regardless of trunk-motion manipulations.

Trunk and arm coordination in the transport component

The PD group produced significantly slower wrist transport movements than the control group, being consistent with numerous previous studies (Alberts et al. 2000; Castiello et al. 1999; Majsak et al. 1998; Rand et al. 2006, 2010; Tresilian et al. 1997). When movement of the trunk did not contribute to the reach, the PD group increased the wrist peak velocity less than the control group. This suggests that PD participants have a limited capability to increase arm reaching speed compared with the controls when the reach-to-grasp task is less complex, thus when the task is performed without involving a trunk movement.

One of the most informative findings of the current study is that the individuals with PD dramatically delayed the onset of trunk motion relative to that of the arm motion, particularly in the conditions where the trunk moved in the direction opposite from the arm reaching (i.e., the trunk flexion with arm flexion and the trunk extension with arm extension, Fig. 3a). Delayed onsets between wrist and trunk motions were previously found in individuals with PD when the prehensile task imposed an unnatural sequencing of a trunk-flexion and an arm-extension motion (Wang et al. 2006). The present study added to the current knowledge that the severity of delayed onset of the trunk motion relative to that of arm motion depends on the combinations of the arm and trunk directions and that the temporal discoordination is magnified when the trunk and the arm move in opposite directions. Furthermore, the individuals with PD had significantly greater temporal variability of trunk onset relative to the arm onset than the controls (Fig. 3c), indicating an unstable coordination between the trunk and arm segments. These results suggest deficient selection and specification of component movements due to PD, resulting in the discoordinated movement initiation (Benecke et al. 1986; Brown and Marsden 1991; Heilman and Valenstein 2012).

It is known that coordination deficits among body segments in individuals with PD are often accentuated when the control demands of a given task are relatively high because of unfamiliarity or reduced automaticity of movements (Connor and Abbs 1991). For example, anti-phase bimanual movements in PD participants show more pronounced coordination deficits between the limbs when compared to in-phase movements (Almeida et al. 2002, 2003; Byblow et al. 2002; Song et al. 2010). Similarly, syncopated finger movements in PD showed a greater temporal variability compared with synchronized finger movements (Stegemöller et al. 2009). In the current study, however, the prolonged delay of trunk-motion onset and its increased variability cannot be explained by such movement unfamiliarity per se. The reason is that the individuals with PD did not always amplify the delay or variability in conditions that involved less familiar patterns (prehension including a trunk extension) as compared to conditions that involved familiar patterns (prehension including a trunk flexion). Furthermore, between the conditions where the trunk and arm moved in the same direction, the trunk-extension, arm-flexion condition (unfamiliar coordination pattern) did not show any amplified delay or variability compared with the trunk-flexion, arm-extension condition (familiar coordination pattern in trunk-assisted prehension).

Instead, the temporal discoordination due to PD was more accentuated in the conditions where the trunk and arm moved in opposite directions. Thus, the critical factor seems to be the discrepancy of the trunk-motion direction relative to the arm reaching direction that is tied to the task goal (i.e., grasping the object). When the trunk movement is prescribed and it is not prerequisite to the task goal, individuals with PD may have difficulty to divide attention between the arm and trunk to properly specify movements. As long as the trunk moves in the same direction as the arm toward the goal, the control system seems to be able to bundle these two segments and specify movements properly. However, when a directional discrepancy between the trunk and arm motions occurs, the control system fails to specify movement of both segments simultaneously.

An important aspect that should not be overlooked is that, between the arm and the trunk segments constituting the transport component, the trunk motion mainly produced substantial temporal discoordination. The PD participants not only delayed the onset of trunk motion but also sometimes initiated the trunk motion in the same direction as the arm and later changed the trunk motion to the prescribed direction. These findings suggest that individuals with PD pay more attention to the arm segment that is tied to the task goal than the axial segment that moves in a different direction from the arm. Such a difficulty may be related to deficits contributing an impediment to maintain attention for two motor tasks, which has been shown in research using dual-task paradigms (Horstink et al. 1990; Van Gemmert et al. 1998). Interestingly, when the dual task involves gait together with an arm-related task, individuals with PD tend to prioritize gait and balance control less compared to healthy adults (Canning 2005; Bloem et al. 2006). Additionally, a recent study reported that goal-directed reaching movements performed by PD participants contain an abnormally greater proportion of an intended task-relevant component in arm joint coordination (Torres et al. 2011, see also Redgrave et al. 2010). Taken together, it is possible that they spend more resources to control a goal-directed arm movement than healthy controls, thereby reducing the resources to control trunk movements.

The observed discoordination in this study may stem from a failed gating mechanism by the basal ganglia. This structure together with associated cortical areas has a significant role in identifying behaviorally relevant events and subsequently selecting upcoming actions (Hikosaka et al. 2000; Smith et al. 2011; Terao et al. 2011; Ueda and Kimura 2003). Such failed selection and gating mechanisms may have caused the observed failure to specify and implement separate motions of the trunk and arm, each of which has a different priority to the task goal. Interestingly, recent studies have demonstrated the importance of cortico-basal ganglia mechanisms in switching from a habitual behavior to a goal-directed behavior (Haggard 2008; Isoda and Hikosaka 2011). Since a habitual behavior usually dominates over other alternative behaviors, a cognitively controlled, goal-directed process occasionally needs to inhibit the habitual behavior, and thus, the habitual action has to be replaced with a non-habitual goal-directed behavior to achieve the task goal. Network of the frontal cortical areas, such as pre-supplementary motor area and lateral prefrontal cortex, and the basal ganglia are presumably involved in such switching (Haggard 2008; Hikosaka and Isoda 2010; Isoda and Hikosaka 2011; Redgrave et al. 2010). Thus, the observed temporal discoordination that was specific to the opposite combinations between the axial- and distal-motion directions may be attributed to an impaired switching function of the cortico-basal ganglia mechanisms from habitual behaviors (i.e., the arm and trunk move to the same direction) to non-habitual controlled behaviors (i.e., the arm and trunk move to the opposite directions).

An additional analysis showed that the UPDRS-III was positively correlated with the magnitude of temporal variability between the trunk and arm movements (Table 3), indicating that the advancement of PD reduces the stability of temporal coordination

between the axial and distal segments within the transport component. As Poizner and colleagues discussed recently (see Levy-Tzedek et al. 2011; Schettino et al. 2006; Tunik et al. 2007), coordinative deficits for multi-part movements are less likely to be amenable to standard anti-Parkinsonian medication therapies (see also Almeida et al. 2003). The reason is that they are likely to rely on specific, time-dependent neural activity, which cannot be readily restored by increasing the gain of the corresponding neural pathway through medication. The present results support this notion, since the on-medicated individuals with PD still showed increased temporal coordination deficits with disease progression.

Coordination between the transport and grasp components

Analysis of the aperture component revealed reduced sensitivity of aperture control in relation to the trunk motion in the PD participants. The older adults increased peak aperture for the trunk-extension conditions, while individuals with PD did not alter grip aperture across different trunk motions (Fig. 2b). Considering that trunk-extension motions were less integrated into the arm motions compared to trunk-flexion motions (Rand et al. 2012), the increased amplitude of grip aperture in the older adults in trunk-extension conditions likely reflects the increase in safety margins for grasping to compensate for an uncertainty of the arm transport (Churchill et al. 2000; Gentilucci et al. 2004; Jackson et al. 1995; Rand et al. 2004; Wing et al. 1986). On the other hand, unchanged peak aperture amplitude in the PD participants reflects a reduced inter-segmental integration between the fingers and trunk.

Similar to the delayed movement initiation observed in the transport component, the individuals with PD delayed the initiation of movements of the grasping component, which is in agreement with previous studies (Castiello et al. 1993; Wang et al. 2006). However, the magnitude of this delay was not influenced by the manipulations of trunk motion, which is in contrast to the onsets of the trunk and arm motions. Aside from the onset delay of finger movements, the individuals with PD were able to maintain the normal temporal coordination between the transport and aperture components (Fig. 4), even though the transport component itself had significant discoordination between the trunk and arm. Given that the trunk motion was not a prerequisite to the goal of the task, it is possible that the individuals with PD prioritized the control of finger and arm movements without fully integrating the trunk motion. As a result, the temporal coordination between the arm and fingers was relatively well preserved.

In summary, the present results support the following three conclusions. (1) Individuals with PD have difficulties to properly coordinate various body segments upon initiation of trunk-assisted goal-directed actions, in particular, when the trunk moves in the direction opposite from the arm. (2) Individuals with PD appear to prioritize control of the arm segment, which is directly related to the task goal, over the trunk segment. (3) The magnitudes of the discoordination and disease severity are related, suggesting that an increase in disease severity leads to an amplification of coordination difficulties. These findings imply that the basal ganglia dysfunction manifested by PD impairs the temporal coordination among the axial and distal body segments, especially when each of them has a different priority to the goal of skilled actions.

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Fig. 1.

Six experimental conditions that prescribed different trunk and arm movements. Participants reached for and grasped a target object by extending (extension) or flexing (flexion) the arm, while trunk-extension, trunk-flexion, or no-trunk motion was executed. The distance between T1 and T2 targets was 20 cm. The drawings show the initial hand locations. The directions of the arm and trunk motions are indicated by the *arrows*

Fig. 2. Mean peak wrist velocity (**a**) and mean amplitude of peak aperture (**b**) for the control and PD groups when the trunk was extended (extension), flexed (flexion), or not involved (no trunk). The *white* and *black columns* refer to the control and PD groups, respectively. *Error bars* refer to the standard errors

Fig. 3.

Effects of changing the trunk and arm movement directions on the time spent from trunk movement onset to wrist movement onset (**a**), its variability [SD] (**c**), the time from peak wrist velocity to peak trunk velocity (**b**), and its variability [SD] (**d**). Trunk-motion manipulations include the trunk-extension condition (extension) and the trunk-flexion (flexion) condition. The white and black circles refer to the control and PD groups, respectively. All values are expressed as a percentage of transport time. Error bars refer to the standard errors

Fig. 4. Relation between the severity of PD (UPDRS-III) and the variability of the time from peak wrist velocity to peak trunk velocity. The variability is expressed as a percentage of transport time. It increases significantly as the UPDRS-III increases ($r = 0.733$, $p < 0.01$)

Table 1

Description of participants with Parkinson’s disease

Patient no.	Age (years)	Gender	Duration (years)	Hoehn and Yahr ^d stage	UPDRS-III ^b	Medication ^c
1	71	f	9	1.5	11	S, M
2	80	m	3	2	14	S
3	72	m	6	3	39.5	S, A
4	77	m	14	4	31	S, M, SE
5	77	m	10	4	29	S
6	78	m	37	2	24	S, ART
7	64	m	10	2.5	16	S, M, AZ
8	71	m	2	1.5	12	S
9	64	f	9	1	9	S, M
10	63	f	2	1.5	8.5	M
11	60	f	18	3	23.5	S, C, A, P
12	76	m	8	2.5	24	ST
13	77	m	27	3	35	S, A
14	86	m	10	3	38	S, A, ART ^d
15	70	f	16	2	32	S, T, A, AZ

^aModified Hoehn & Yahr stage scale (Hoehn and Yahr 1967; see also Goetz et al. 2004)

^bUPDRS motor examination score (Fahn et al. 1987)

^cA amantadine, ART artane, AR aricept, AZ azilect, C comtan, M mirapex, P permax, R requip, S sinemet, SE Selegiline, ST Stalevo, T tasmar

^dAricept was prescribed to patient 14 for balance and fall problems, not because of suspected dementia (see for the beneficial effects of Aricept (donepezil) on falls in PD, for example, Chung et al. (2010) and Kim et al. (2013))

Table 2

Effect of trunk- and arm-motion conditions on kinematic parameters related to the transport component

	Trunk motion		Arm motion		ANOVA results
	No trunk	Extension	Flexion	Extension	Flexion
<i>Arm movement</i>					
Transport time (ms)					
Control	725 (44)	854 (56)	851 (61)	808 (53)	812 (52)
					G: $F = 8.33^{**}$, $\eta_p^2 = 0.22$
PD	1,062 (99)	1,226 (125)	1,196 (121)	1,155 (117)	1,168 (111)
					T: $F = 22.12^{***}$, $\eta_p^2 = 0.43_{a,b}$
Peak wrist velocity (mm/s)					
Control	584 (37)	502 (32)	507 (34)	530 (32)	532 (37)
					G: $F = 10.27^{**}$, $\eta_p^2 = 0.26$
PD	416 (25)	377 (29)	382 (28)	394 (28)	388 (28)
					T: $F = 35.01^{***}$, $\eta_p^2 = 0.55_{a,b}$
					GT: $F = 4.77^*$, $\eta_p^2 = 0.41$
					TA: $\varepsilon = 0.83$, $F = 3.91^*$, $\eta_p^2 = 0.12$
Time to peak wrist velocity (%)					
Control	42.3 (1.3)	44.9 (1.4)	41.6 (1.4)	44.5 (1.3)	41.4 (1.3)
					T: $F = 8.12^{**}$, $\eta_p^2 = 0.22_{a,c}$
PD	39.5 (1.2)	43.3 (1.6)	41.4 (0.9)	42.5 (1.5)	40.4 (0.9)
					A: $F = 8.44^{**}$, $\eta_p^2 = 0.23$
					TA: $F = 3.92^*$, $\eta_p^2 = 0.12$
<i>Trunk movement</i>					
Peak trunk velocity (mm/s)					
Control	-	206 (13)	204 (14)	208 (12)	202 (12)
					G: $F = 8.55^{**}$, $\eta_p^2 = 0.23$
PD	-	151 (16)	147 (16)	152 (17)	146 (15)
Duration from trunk onset to wrist onset (%)					
Control	-	1.6 (0.9)	-1.4 (0.8)	-0.8 (0.9)	1.0 (0.8)
					G: $F = 3.57^{+}$, $\eta_p^2 = 0.11$
PD	-	-4.4 (3.4)	-9.0 (5.8)	-4.7 (3.4)	-8.7 (5.3)
					TA ¹ : $F = 9.40^{**}$, $\eta_p^2 = 0.25$

Trunk motion			Arm motion		ANOVA results
No trunk	Extension	Flexion	Extension	Flexion	
Duration from peak wrist velocity to peak trunk velocity (%)					
Control	-	14.9 (3.8)	16.5 (2.0)	16.0 (2.8)	15.4 (3.1)
PD	-	21.1 (8.1)	26.5 (8.8)	20.0 (7.1)	28.0 (9.7)
					GTA: $F = 4.79^*$, $\eta_p^2 = 0.14$
					TA [†] : $F = 4.34^*$, $\eta_p^2 = 0.13$
					GTA: $F = 4.27^*$, $\eta_p^2 = 0.13$

Mean (SE); % Values are expressed as a percentage of transport time

ε Huynh-Feldt's epsilon, G group, $df = 1,29$, T trunk motion, $df = 2,58$, A arm motion, $df = 1,29$, TA , TA [†] trunk motion $\times$ arm motion interaction $df = 2,58$, $df = 1,29$, respectively, GTA group $\times$ trunk motion interaction, $df = 2,58$; GTA group $\times$ trunk motion $\times$ arm motion interaction, $df = 1,29$

* $p < 0.05$;

** $p < 0.01$;

*** $p < 0.001$;

[†] $0.05 < p < 0.1$

^a $p < 0.05$ (post hoc test) between no trunk and trunk extension;

^b between no trunk and trunk flexion;

^c between trunk extension and trunk flexion

Table 3

Correlation coefficients between UPDRS-III and the variability (i.e., SD) of temporal coordination

	Trunk extension Arm extension	Trunk extension Arm flexion	Trunk flexion Arm extension	Trunk flexion Arm flexion
Duration variability of the time from trunk onset to wrist onset	0.564 [*]	0.349	0.322	0.456 ⁺
Duration variability of the time from peak wrist velocity to peak trunk velocity	0.511 ⁺	0.392	0.295	0.733 ^{**}

 $N = 15$;^{*}
 $p < 0.05$;^{**}
 $p < 0.01$;⁺
 $0.05 < p < 0.1$

Table 4

Effect of trunk- and arm-motion conditions on kinematic parameters related to the grip aperture component

	Trunk motion		Arm motion		ANOVA results
	No trunk	Extension	Flexion	Extension	Flexion
Amplitude of peak aperture (mm)					
Control	50 (4)	54 (4)	51 (4)	48 (3)	54 (4)
					G: $F = 3.19^+$, $\eta_p^2 = 0.10$
PD	45 (1)	45 (2)	44 (1)	41 (1)	47 (1)
					T: $F = 5.26^{**}$, $\eta_p^2 = 0.15_{a,c}$
					A: $F = 48.21^{***}$, $\eta_p^2 = 0.62$
					GT: $F = 4.92^*$, $\eta_p^2 = 0.15$
Hand-target distance for aperture closure initiation (mm)					
Control	21 (3)	26 (4)	20 (3)	24 (4)	21 (3)
					T: $F = 4.22^*$, $\eta_p^2 = 0.13_c$
PD	17 (2)	17 (2)	15 (2)	18 (3)	14 (2)
					A: $F = 4.15^+$, $\eta_p^2 = 0.13$
Time to grip aperture onset (%)					
Control	11.8 (1.1)	12.2 (1.7)	12.5 (1.5)	13.5 (1.3)	10.9 (1.5)
					G: $F = 5.08^*$, $\eta_p^2 = 0.15$
PD	17.4 (2.6)	17.3 (2.3)	19.3 (2.6)	19.0 (2.4)	17.0 (2.6)
					A: $F = 3.91^+$, $\eta_p^2 = 0.12$
Time to peak grip aperture (%)					
Control	69.7 (1.8)	70.3 (2.0)	70.4 (1.7)	70.9 (1.7)	69.4 (2.0)
					T: $F = 3.23^*$, $\eta_p^2 = 0.10_b$
PD	68.3 (2.2)	71.5 (1.9)	71.7 (1.6)	70.3 (2.1)	70.7 (1.5)
					TA: $F = 3.64^*$, $\eta_p^2 = 0.11$
Duration from peak wrist velocity to peak grip aperture (%)					
Control	27.4 (2.4)	25.4 (2.6)	28.9 (2.5)	26.5 (2.3)	28.0 (2.7)
					T: $F = 4.32^*$, $\eta_p^2 = 0.13_c$
PD	28.8 (1.5)	28.1 (1.4)	30.3 (1.3)	27.8 (1.7)	30.3 (1.1)
					A: $F = 3.15^+$, $\eta_p^2 = 0.10$

Mean (SE); % Values are expressed as a percentage of transport time

G group, $df = 1,29$, T trunk motion, $df = 2,58$, A arm motion, $df = 1,29$, TA trunk motion $\times$ arm motion interaction $df = 2,58$, GT group $\times$ trunk motion interaction, $df = 2,58$

* $p < 0.05$;
 ** $p < 0.01$;
 *** $p < 0.001$;
⁺ $0.05 < p < 0.1$
^a $p < 0.05$ (post hoc test) between no trunk and trunk extension;
^b between no trunk and trunk flexion;
^c between trunk extension and trunk flexion