Effects of a moving target versus a temporal constraint on reach and grasp in patients with Parkinson’s disease

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Abstract

The reaction times and kinematics of reach and grasp were analyzed for eight subjects with Parkinson’s disease (PD) and eight healthy subjects during three variations of a maximal speed prehension task: (a) grasping a stationary ball as fast as possible, (b) grasping a stationary ball within specific time constraints (520 ms and 450 ms), and (c) grasping a moving ball within the same time constraints. Subjects with PD exhibited bradykinesia when reaching for a stationary ball. When reaching for a moving or stationary ball with temporal constraints, subjects with PD moved as fast as healthy subjects. The reaction times of both groups were shorter when reaching to a moving ball than to a stationary ball, regardless of the time constraint. Subjects with PD had a slower velocity of hand opening and closing, a smaller maximal aperture, and a longer time to maximal aperture than healthy subjects in all task conditions. Thus, visual motion cues and external temporal constraints had a greater effect on reach than on grasp. The results suggest that the bradykinesia observed in individuals with PD during self-determined maximal speed prehension may reflect a strategy used to compensate for deficiencies in the grasp component of the task.

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Introduction

The degree to which bradykinesia occurs in Parkinson’s disease (PD) is largely dependent upon the conditions of the task being performed. A number of studies have shown that subjects with PD display less bradykinesia when they move in response to auditory or visual cues than when they perform self-determined, maximal speed movements (e.g., Cooke et al., 1978; Freeman et al., 1993; Georgiou et al., 1993, 1994; Morris et al., 1994a,b, 1996; Thaut et al., 1996; Kelly et al., 2002; Nowak and Hermsdorfer 2006). This suggests that bradykinesia reflects an impairment in the internal regulation of motor output.

In agreement with these findings, we previously reported that subjects with PD displayed bradykinesia when they reached for a stationary ball, but not to a moving ball (Majsak et al., 1998). There are three possibilities as to why the subjects reached faster under the moving ball condition. First, their increased reaching speed may simply have been due to the introduction of an external time constraint. Previous studies of PD showed that movement speed increased with the introduction of verbal temporal feedback (e.g., Teasdale et al., 1990), visual cues (e.g., Cooke et al., 1978; Georgiou et al., 1993, 1994; Morris et al., 1994a,b, 1996; Kelly et al., 2002; Sidaway et al., 2006) or auditory timing cues (e.g., Freeman et al., 1993; Thaut et al., 1996; Ma et al., 2004; Nowak and Hermsdorfer 2006). A second possibility is that the visual stimulus of the moving ball had a direct effect on reaching speed by engaging neural circuits sensitive to visual cues that are unaffected by PD (e.g., Orban, 1985; Glickstein and Stein, 1991; Zeki et al., 1991; Sunaert et al., 1999). Third, subjects with PD may have reached faster because of negative consequences from reaching too slowly: failure to grasp the ball. Accordingly, they may have been more attentive to the task when the ball was available only for a limited time. It is well known that individuals with PD improve their performance when they focus their attention on a motor task, and that a deterioration in performance occurs when attentional
resources are challenged (e.g., Benecke et al., 1986, 1987; Brown and Marsden, 1988a,b, 1991; Morris et al., 1996; O’Shea et al., 2005; Azulay et al., 2006).

Although results from our previous study demonstrated that subjects with PD moved faster when reaching for a moving ball, they had a higher number of unsuccessful grasps than healthy subjects. Thus, their overall level of performance was not as good as healthy subjects. It is possible that the unsuccessful grasps of subjects with PD resulted from an inability to quickly generate an appropriate grasp, or to coordinate reach and grasp. A number of abnormalities in the reach and grasp of subjects with Parkinson’s disease have been previously reported. Wrist velocities are slower, a greater proportion of movement time is spent in deceleration (Müller and Stelmach, 1992; Bennett et al., 1995), and peak grip aperture is often smaller and occurs later in reach (Castiello et al., 1993; Bennett et al., 1995). These characteristics are often more pronounced when subjects are instructed to move as fast as possible (Müller and Stelmach, 1992; Jackson et al., 1995). Furthermore, tasks requiring coordination of multiple body segments seem to be particularly affected (e.g., Poizner et al., 2000; Santello et al. 2004; Schettino et al., 2004; Muratori et al., in press).

In the present study, subjects reached and grasped a ball under three conditions. In the first condition, subjects reached for a stationary ball as fast as possible. In the second, subjects reached for a moving ball. In the third, subjects had to reach and grasp a stationary ball before it dropped out of reach. The last condition necessitated an increase in speed in the absence of a moving stimulus. Comparison between these three conditions provided a means of assessing whether the increase in prehensile speed was due to an external time constraint alone or was due to the visual stimulus associated with the moving target. In addition, the grasp kinematics was analyzed to determine whether failures to grasp the ball were due to impairments in grasp or the coordination between reach and grasp. We hypothesized that subjects with PD would increase their reaching speed to the stationary ball when time constraints were imposed, but would remain slower than healthy subjects. In addition, we predicted that subjects with PD would match the reaching speed of healthy subjects when responding to the visual motion stimulus of the moving ball. Finally, we expected that subjects with PD would have abnormalities in grasp and/or the coordination between reach and grasp when reaching under time constraints.

Methods

Subjects

Eight subjects diagnosed with Stage 3 (Hoehn and Yahr, 1967) idiopathic PD (6 male, 2 female, mean age 70.4±3.7 years) and eight healthy age-matched control subjects (4 male, 4 female, mean age 68.8±4.4 years) with no prior history of neurological impairment participated in this study after providing their informed consent. All subjects were right-handed and without visual impairments, other than the use of eyeglasses. Criteria for exclusion from the study were resting tremor, dyskinesia during the medicated state, a documented history of right upper limb trauma, neurological impairment other than PD, or a documented history of psychological disturbances requiring pharmacological management. The motor section of the Unified Parkinson’s Disease Rating Scale (UPDRS, Fahn and Elton, 1987) was used to grade the motor performance of subjects prior to testing. The Modified Mini-Mental Status Exam (Stern et al., 1987) was used to confirm that subjects did not have a cognitive impairment that would impact their ability to understand the task (a score >35).

Since we were mainly interested in the pathological effects of PD on reach-to-grasp under various externally-driven conditions, all subjects with PD were undergoing neuropharmacological treatment (Table 1). Subjects with PD were tested first thing in the morning prior to their initial dose of medication (12 h following their last dose, i.e., practically defined OFF state).

Table 1 provides the subject characteristics of the PD group. The study was approved by the Teachers College, Columbia University Institutional Review Board.

Apparatus and procedures

Prior to testing, all subjects were oriented to the setup and purpose of the study. Infrared reflecting markers were attached to the thumbnail, fingernail of the long finger, the dorsal surface of the second metacarpal–phalangeal joint, and the dorsal surface of the radius of the right wrist.

The upper limb was positioned with the shoulder in 0° of flexion, the elbow in 90° of flexion, the forearm in 0° pronation, and the tips of the thumb and first two fingers placed together. The upper trunk was stabilized against the back of the chair with a soft elastic band to minimize trunk displacement. The task required subjects to reach and grasp a ball (6.8 cm diameter, covered with infrared reflecting tape) in a designated contact zone (10 cm in length) that was located at the lower end of an inclined ramp (2.5 cm × 233 cm). The ramp was placed parallel to the frontal plane of subjects at a distance equal to 90% of arm length. The height and position of the ramp was set so that the contact zone was located in front of the right shoulder at mid-trunk level (see Fig. 1). The use of a pre-determined contact zone ensured that subjects reached to grasp the ball at the same relative ramp position regardless of whether the ball was stationary or moving. Placing the contact zone at the end of the ramp prevented subjects from grasping the moving ball late, as the ball fell off the ramp and behind a barrier after it passed beyond this zone.

Subjects were tested under three conditions: (a) stationary ball — reach as fast as possible to grasp a ball placed within the contact zone, (b) drop ball — reach to grasp a stationary ball that dropped from view after a pre-determined time, and (c) moving ball — reach to grasp a moving ball from within the contact zone. The stationary ball condition was always presented first, as it served as a baseline measure of the subjects’ maximal reaching speed. It was also presented after the drop ball and moving ball conditions to determine whether any effects of these conditions persisted after experiencing these conditions. In the stationary ball and drop ball conditions subjects were instructed to reach as quickly as possible following the illumination of a red light (1.5 cm × 2.0 cm) mounted below the center of the contact zone.
In the drop ball condition, the time between the start signal and the time the ball dropped from view defined the time constraints for successful ball grasp. In the moving ball condition, the time constraint started with the appearance of the ball rolling down a ramp from behind a barrier and ended when the ball entered the contact zone.

Subjects were tested under a 520 ms and a 450 ms time constraint. We previously showed that subjects with PD could successfully grasp a moving ball 50% of the time under a 520 ms time constraint, which was 30% shorter than the time these subjects used to perform a maximal speed grasp of a stationary ball (Majsak et al., 1998). A 450 ms time constraint was used to challenge the maximal reaching speed of healthy subjects to a similar degree, as this was 30% shorter than the average reaching time healthy subjects used to perform a maximal speed reach in our previous study.

To create a 520 ms temporal constraint in the moving ball condition the ball was released on the ramp 10 cm behind the edge of the barrier. This resulted in a ball velocity of 0.38 m/s at the edge of the barrier and 2.30 m/s by the time the ball entered the contact zone. For the time constraint of 450 ms, the ball was released 20 cm from the edge of the barrier. Ball velocity was 0.89 m/s at the edge of the barrier and 3.11 m/s at the contact zone.

For each condition, a computer-generated tone served as a ready signal. The time between the tone and the start of a trial varied randomly between one and five seconds to minimize anticipation of trial initiation. Catch trials (tone given, but no trial initiated) were also randomly introduced (16% of total trials). If subjects began their reach before a trial was initiated or failed to reach for the ball, the trial was repeated.

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### Table 1

Subject characteristics of the Parkinson’s disease group

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (years)</th>
<th>Gender</th>
<th>MMMS score</th>
<th>Disease stage (Hoehn &amp; Yahr)</th>
<th>Time since disease onset (years)</th>
<th>UPDRS score</th>
<th>Medication</th>
<th>Average daily Dosage (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>74</td>
<td>Male</td>
<td>48</td>
<td>III</td>
<td>4</td>
<td>34</td>
<td>Sinemet</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eldepryl</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tasmar</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>75</td>
<td>Male</td>
<td>50</td>
<td>III</td>
<td>6</td>
<td>37</td>
<td>Sinemet</td>
<td>550</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eldepryl</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tasmar</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>70</td>
<td>Male</td>
<td>57</td>
<td>III</td>
<td>3</td>
<td>32</td>
<td>Rasagiline</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>72</td>
<td>Male</td>
<td>47</td>
<td>III</td>
<td>5</td>
<td>31</td>
<td>Sinemet</td>
<td>300</td>
</tr>
<tr>
<td>5</td>
<td>72</td>
<td>Male</td>
<td>38</td>
<td>III</td>
<td>2</td>
<td>32</td>
<td>Sinemet</td>
<td>650</td>
</tr>
<tr>
<td>6</td>
<td>70</td>
<td>Female</td>
<td>44</td>
<td>III</td>
<td>8</td>
<td>20</td>
<td>Sinemet</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eldepryl</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Carbidopa</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>65</td>
<td>Male</td>
<td>41</td>
<td>III</td>
<td>25</td>
<td>45</td>
<td>Sinemet</td>
<td>800</td>
</tr>
<tr>
<td>8</td>
<td>65</td>
<td>Female</td>
<td>49</td>
<td>III</td>
<td>5</td>
<td>33</td>
<td>Amantidine</td>
<td>200</td>
</tr>
</tbody>
</table>
Two practice trials were provided prior to each condition. Subjects performed five blocks of four trials, first under the 520 ms time constraint and then the 450 ms time constraint. A block of trials with the stationary ball was always presented first, followed by a block of moving ball trials, a second block of stationary ball trials to assess for carry-over effects, a block of drop ball trials, and a final block of the stationary ball trials. Verbal cues to reach as fast as possible were given to subjects prior to each trial in the stationary and drop ball conditions. Following each valid test trial, the experimenter documented the reaction time of the subject and whether ball grasp was successful. Five-minute rest periods were provided between trials blocks and fifteen minutes of rest was provided between testing at the 520 ms and 450 ms time constraints. The total testing time for subjects was approximately 90 min.

Data processing and analysis

A four-camera Motion Analysis® system (Santa Rosa, CA) was used to track ball position and to collect 3-D kinematic data of reach and grasp at 120 Hz. The cameras were placed in a semicircle around subjects. Movement data for each marker was filtered at 6 Hz using a dual pass second-order Butterworth digital filter. The displacement of the wrist marker was used to derive hand paths and the kinematics of reaching. The thumb, long finger, and second metacarpal–phalangeal joint markers were used to analyze grasp kinematics. Tangential velocity of the wrist and angular velocity of hand opening and closing were calculated by differentiating wrist and finger displacements, respectively. The onset of reach was defined as the time when the tangential velocity of the wrist exceeded 2.5 cm/s for three successive data samples. Reach termination in the stationary and drop ball conditions was defined as the time when the ball was displaced in the X- or Y-plane for three successive data samples. Reach termination in the moving ball condition was the time when the ball was displaced forward in the X-plane from its path on the ramp, or when a decrease in tangential velocity occurred for three successive data samples. When subjects completely missed the moving or drop balls, the end of reach was defined as the time when wrist position in the X-plane matched the mean X-coordinate of the wrist at ball contact in the stationary ball condition.

We were primarily interested in how the reach and grasp speeds were affected by the experimental conditions. To determine this the movement time, peak wrist velocity, velocity at reach termination, acceleration time and the percentage of movement time spent in deceleration were measured (see Majsak et al. 1998). We also measured the peak angular velocity of hand opening and closing and the maximal aperture and aperture at end of reach to determine whether they differed between subjects with PD and controls. Coordination of reach and grasp was measured by the time of grasp initiation, time to maximal aperture relative to reach initiation, and peak velocities of hand opening and closing. Hand aperture was defined by the angle created by the markers on the thumb, second metacarpal–phalangeal joint, and middle finger, and was calculated as the observed angle minus the initial starting angle when the fingers were closed. Onset of hand opening was defined as the time when initial hand opening increased by more than one degree.

Subjects could use a variety of orientations of the thumb, fingers, and wrist to intercept the ball in a range of locations within the 10 cm contact zone. Consequently, reaching accuracy was categorized as either successful or unsuccessful contact with the ball, rather than a movement to a specific point in space. Unsuccessful grasps were sub-divided into: (1) slips — ball contact with the thumb and fingers followed by the ball slipping out from between the thumb and fingers, (2) deflections — deflection of the ball with the hand, thumb, or one or more fingers, and (3) misses — no contact with the ball. Comparisons between the frequencies of unsuccessful ball grasps for groups within the moving and drop ball conditions was analyzed through a Mann–Whitney U Test (p<0.05).

The means of the kinematic measures of each subject were typically based on four trials per condition. However, upon analysis of the raw data, a number of trials had to be rejected because a marker had been obscured from camera view prior to the end of reach. In that case, the means were computed from the remaining trials. One of the control subjects had two unusable trials in the drop condition at 450 ms, and another control subject had two unusable trials in the moving ball condition at 520 ms. The remaining subjects had at least three usable trials in each condition.

Analysis was carried out in three ways. First, we evaluated whether kinematic distinctions could be made between successful and unsuccessful grasps. The means of the kinematic variables for subjects who had both successful and unsuccessful grasps in any of the moving or drop ball conditions were analyzed using a 2 (group)×2 (grasp result) analysis of variance (ANOVA). Second, the trials of all subjects were collapsed across successful and unsuccessful grasps and used to compute group means for each condition. These means were analyzed using a 2 between group (PD vs. controls)×5 conditions (stationary ball 1, moving ball, stationary ball 2, ball drop, stationary ball 3)×2 Constraint Time (450, 580) ANOVA with repeated measures of the second and third factors. Newman–Keuls multiple comparison tests (p<.05) were used where appropriate. Separate analyses were carried out on the kinematics of the successful and unsuccessful grasps in the moving and drop ball conditions, using paired-sample t-tests (p<0.05).

Results

Distinct changes in the reach and grasp characteristics were observed when subjects with PD performed the tasks under the 520 ms time constraint. Other than an increased frequency of misses, no additional changes were observed in the reach and grasp characteristics when the time constraint was decreased to 450 ms. Consequently, only the results from the 520 ms constraint will be reported for the subjects with PD. Furthermore, the stationary ball conditions did not differ from each other (suggesting no carry over) in any instance. Therefore for illustrative purposes only the first stationary condition is depicted in figures.

Fig. 2 shows the reaching velocity profiles and grasp apertures of a subject with PD and a healthy subject during the
stationary ball condition and the two conditions under the 520 ms time constraint. When subjects reached as fast as possible to the stationary ball the reaching and grasping speeds of subject with PD was slower than the healthy subject, and the hand apertures were smaller with a longer time to maximal aperture. The subject with PD generated faster reaches in response to both the moving and ball-drop conditions, but the healthy subject did not. Interestingly, the grasp speeds of subject with PD remained slower and hand apertures remained smaller than those of the healthy subject in all conditions. As described below, these results were representative of the subjects we tested.

**Task performance**

Although all subjects accurately terminated their reach within the contact zone, occasional unsuccessful grasps occurred. When reaching under a 520 ms time constraint, subjects with PD had higher frequencies of unsuccessful grasps than healthy subjects for both the drop (70% versus 0%, respectively; \( U(16)=1.5, p<0.05 \)) and moving ball conditions (40% versus 25%, respectively; \( U(16)=16.5, p<0.05 \)) (Table 2). The data for unsuccessful grasps of the stationary ball were collapsed over the three blocks of this condition.

The unsuccessful grasps of subjects with PD were primarily due to deflections of the moving ball and complete misses of the drop ball. In an attempt to determine the reason subjects failed to grasp the ball, statistical comparisons \((t\)-tests\) were made between successful and unsuccessful ball grasps of reaction time, movement time, reach and grasp kinematics, and the coordination of reach and grasp. No significant differences were observed for any measure.

**Does reaching behavior change in response to visual and temporal constraints?**

No significant differences were observed between groups in reaction time for any of the task conditions. As seen in Fig. 3, the reaction times were significantly shorter when reaching to the moving ball than to the stationary and drop balls for both groups \( F(4,56)=23.43, p<0.01 \; \text{eta}^2=0.626 \). The reaching behavior

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**Table 2**

Types and incidences of unsuccessful ball grasps

<table>
<thead>
<tr>
<th>Condition</th>
<th>Group</th>
<th>Slips</th>
<th>Deflections</th>
<th>Misses</th>
<th>Incidences</th>
<th>Medians (and ranges)</th>
<th>Significance level of group differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>520 ms time trials:</td>
<td>Control</td>
<td>3</td>
<td>–</td>
<td>–</td>
<td>3</td>
<td>0 (0–1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Parkinson’s disease</td>
<td>4</td>
<td>–</td>
<td>–</td>
<td>4</td>
<td>0 (0–2)</td>
<td>NS</td>
</tr>
<tr>
<td>Moving (32 trials/group)</td>
<td>Control</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>1 (0–2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Parkinson’s disease</td>
<td>–</td>
<td>11</td>
<td>2</td>
<td>13</td>
<td>2 (0–3)</td>
<td>&lt;.05</td>
</tr>
<tr>
<td>Drop (32 trials/group)</td>
<td>Control</td>
<td>–</td>
<td>–</td>
<td>3</td>
<td>3</td>
<td>0 (0–1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Parkinson’s disease</td>
<td>1</td>
<td>6</td>
<td>18</td>
<td>25</td>
<td>3.5 (1–4)</td>
<td>&lt;.01</td>
</tr>
</tbody>
</table>

\( ^a \) Data for stationary conditions is collapsed across all 3 blocks.
of subjects with PD differed from healthy subjects in several aspects. Subjects with PD had longer movement times than healthy subjects when reaching to a stationary ball (see Fig. 3), but not when reaching to a moving or drop ball [group × condition interaction, $F(4,56)=6.57, p<0.01; \eta^2=0.319$]. Subjects with PD also had significantly longer acceleration times than healthy subjects for reaches to the stationary and drop balls. Subjects with PD had higher peak velocities when reaching to the moving ball than to the stationary ball [$F(4,56)=2.57, p<0.05$], but no differences were seen when reaching to the drop ball. In contrast, healthy subjects showed no significant change in peak wrist velocity across task conditions [group × condition interaction, $F(4,56)=3.14, p<0.05$]. Both groups showed similar deceleration patterns when external temporal constraints were present. When reaching to the moving and drop balls, all subjects had higher wrist velocities at the end of reach $F(4,56)=41.88, p<0.01; \eta^2=0.749$ and a smaller percentage of time was spent in deceleration $F(4,56)=17.39, p<0.01; \eta^2=0.554$. Although subjects with PD showed a trend of decreasing their movement time over the three blocks of stationary ball trials, this trend was not statistically significant.

To summarize, when moving and drop ball constraints were present, movement times decreased for subjects with PD but not controls, resulting in comparable reaching speeds. A moving ball had a greater effect than a drop ball on the time to peak velocity for both groups and on peak velocity for subjects with PD.

**Does grasp behavior change in response to visual/temporal constraints?**

Compared to the healthy subjects, subjects with PD showed a number of differences in their grasp kinematics and coordination of reach and grasp. As illustrated by the representative aperture profiles in Fig. 2 and the group data in Fig. 4, subjects with PD displayed smaller maximal apertures [$F(1,14)=14.88, p<0.01; \eta^2=0.515$], a longer time to maximal aperture [$F(1,14)=9.43, p<0.01; \eta^2=0.402$] (not shown), and lower peak velocities of hand opening [$F(1,14)=8.35, p<0.05; \eta^2=0.374$] and closing [$F(1,14)=9.59, p<0.01; \eta^2=0.406$] across task conditions. Subjects with PD also showed a greater latency between the start of reach and the initiation of hand opening across all
conditions $[F(1,14)=10.57, p<0.01; \eta^2=0.430]$. However, no significant group difference was found when this delay was analyzed as a percentage of reaching time.

Despite their altered patterns of grasp and coordination of reach and grasp, subjects with PD retained some ability to modulate their grasp in relation to task demands. All subjects

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Fig. 4. Means and standard deviations for grasp kinematics for the control subjects and subjects with PD group: A) maximal aperture, (B) peak angular velocity of hand opening, and (C) peak angular velocity of hand closing. S1, S2, S3 = Stationary ball conditions, M = Moving ball conditions (520 ms time constraint), and D = Drop ball conditions (520 ms time constraint), $^*p<0.05$. 
had a larger maximal aperture when they reached to the moving ball than to the drop or stationary balls. Both groups also showed a significantly larger aperture at the end of reach to the moving ball than to the stationary and drop balls [$F(4,56)=22.76$, $p<0.01$; $\eta^2=0.619$]. Similarly, the velocity of hand opening for all subjects was significantly higher to the moving ball and drop ball than to the stationary ball [$F(4,56)=24.40$, $p<0.01$; $\eta^2=0.635$].

**Does the reach and grasp behavior of healthy subjects resemble that of subjects with PD when their maximal reaching speeds are equally challenged?**

Decreasing the time constraint of the moving ball to 450 ms for healthy controls resulted in a median incidence of unsuccessful grasps (40%) that was comparable to subjects with PD under the 520 ms time constraint (41%). The median incidence of unsuccessful grasps of the drop ball was also higher for controls (50%), although slightly lower than the incidence in subjects with PD during the 520 ms trials (70%). Similar to the pattern shown by subjects with PD in the 520 ms trials, the unsuccessful grasps of controls were dominated by deflections of the moving ball and complete misses of the drop ball.

Reaction times to the drop and moving balls did not change when the time constraint was reduced to 450 ms. The reaching patterns of healthy subjects under the 450 ms constraint were similar to those under the 520 ms time constraint. The primary difference was that healthy subjects reduced their acceleration time [$F(1,14)=9.45$, $p<0.01$; $\eta^2=0.403$] for both conditions. No consistent changes were observed for movement time, peak wrist velocity, contact velocity, or percentage of time in deceleration. Similarly, no consistent differences in grasp kinematics were observed between the different constraint times.

**Discussion**

The present study extends our previously reported findings by showing that simply imposing time constraints on subjects with PD was sufficient to drive the motor system faster. In our previous study (Majsak et al., 1998) we were unable to determine whether it was the visual motion stimulus of a moving ball or the temporal constraint defined by the time available to grasp the ball that caused faster reaching. By separating the time constraint from the visual motion stimulus, we were able to determine that time constraints alone can increase movement speed. The effect of time constraints appears to be unique to subjects with PD. When healthy subjects were similarly challenged by imposing a 450 ms time constraint, no further increases in movement speed were observed.

**External cues increase reaching speed in PD**

Earlier studies showed that individuals with PD could move faster when provided verbal feedback (e.g., Teasdale et al., 1990) or auditory cues (e.g., Thaut et al., 1996), but in these studies normal movement speeds were not attained. Ballanger et al. (2006) showed that the reaction times and movement times of both subjects with PD and healthy subjects performing a button press task could be reduced if an acoustic cue were given and further reduced if a task consequence was added for slow reaction times and movement times.

In the present study, the drop ball was as effective as the moving ball for decreasing movement time. However, there were unique effects associated with the visual motion stimulus. Subjects with PD had higher peak velocities when reaching to the moving ball. In addition, reaction time was faster when reaching to the moving ball as compared to the drop ball for all subjects. Schenk et al. (2003) also noted that a visual motion stimulus sped up movement initiation for both healthy and subjects with PD. Thus, visual motion stimuli can induce a faster activation of the motor system than temporal constraints alone, regardless of basal ganglion function. As previously suggested (e.g., Orban, 1985; Glickstein and Stein, 1991; Zeki et al., 1991; Majsak et al., 1998; Sunaert et al., 1999), visual motion stimuli may engage neural circuits sensitive to visual cues that are less affected by PD. The difference between stationary and moving stimuli might also be explained in predictive/responsive terms where subjects with PD have impaired predictive control of grasp (e.g., Santello et al., 2004; Muratori et al., in press) but respond more normally when reacting to a stimulus (see Flower, 1978).

Our findings concerning the grasp component of the task are consistent with reports indicating that individuals with PD have impaired grasp control and a disruption of the normal timing relationship between reach and grasp (e.g., Castiello et al., 1993; Scarpa and Castiello, 1994; Bennett et al., 1995; Gordon et al., 1997; Ingvarsson et al., 1997; Schenk et al., 2003; Santello et al. 2004; Muratori et al., in press). Our results are in agreement with other studies showing that subjects with PD have slow hand opening and closing with hypometria (Castiello et al., 1993, 1999; Castiello and Bennett, 1994; Gentilucci and Negrotti, 1999; Schenk et al., 2003), and a prolonged time to maximal aperture during reaching (Bennett et al., 1995; Alberts et al., 2000; Schettino et al., 2004, 2006; Rand et al., 2006).

**Differential effects of external cues on reach and grasp**

The reach and grasp components of subjects with PD appear to be differentially affected by time constraints. When subjects with PD reached for the moving and drop ball, their movement time decreased and was similar to that of healthy subjects. Although the grasp kinematics of subjects with PD were modulated when time constraints were imposed, significant deficits remained compared to the healthy subjects. Under both time constraints, subjects with PD consistently showed a smaller maximal aperture, slower hand opening and closing, and a later time of maximal aperture relative healthy subjects. These findings are similar to those reported by Schenk et al. (2003), who showed subjects with PD matched the reaching speeds, but not the grasp speeds of healthy subjects when reaching for a moving object. A decoupling between reach and grasp occurs in healthy subjects when the size or location of an object is perturbed at the initiation of reach (e.g., Castiello et al., 1992, 1993; Gentilucci et al., 1991; 1992; Paulignan et al., 1991a,b).
Reach and grasp are also reported to be differentially affected by changes in object velocity when prehension tasks involve the acquisition of moving objects (Chieffi et al., 1992; Laurent and Montagne, 1993, Mason and Carnahan, 1999). Parallel but separate visuomotor channels have been proposed to control of reach and grasp (e.g., Jeannerod, 1984; Gentilucci et al., 1988; Rizzolati et al., 1988). Thus, although the reach and grasp components of prehension are functionally coupled, they appear to be independently regulated.

A number of studies have shown that the natural coupling mechanisms that exist between reach and grasp are disrupted as a consequence of PD (e.g., Bennett et al., 1993, 1995; Castiello and Bennett, 1994; Castiello et al., 1993; 1999; Schettino et al., 2004, 2006). The finding that the moving and drop balls had a robust effect on limb transport and minimal effect on grasp supports the theory that reach and grasp are independently controlled. The slower reaching displayed by subjects with PD during self-paced prehension may reflect a strategy in which contact with the ball was delayed to ensure a successful grasp. Although subjects with PD were able to speed up their reach to the moving and drop balls, they had high incidences of unsuccessful grasps. Many of these unsuccessful grasps were due to deflections of the ball off the palm or fingers, suggesting impairments in the performance and timing of grasp. Thus, in the absence of a time constraint, subjects with PD may have slowed their reaching to compensate for impairments in grasp.

Conclusions and clinical implications

The present findings suggest that the bradykinesia of individuals with PD may be the result of a compensatory movement strategy for abnormal grasp control (e.g., Latash and Anson, 1996), or an impairment in movement coordination, rather than a physiological deficit in the ability to generate high levels of force (e.g., Hallett and Khoshbin, 1980; Godaux et al., 1992; Corcos et al., 1996). They are able to reach quickly, but only when temporal constraints are imposed on their actions. Furthermore, they have impairments of grasp control and an abnormal pattern in the coordination of reach and grasp. The reach component can be sped up via external cues, with the visual (moving ball) condition being particularly robust. However, corresponding changes were not observed in grasp (see Schettino et al., 2006).

Our results support and extend previous findings that the motor behavior of individuals with Parkinson’s disease is task specific (Kelly et al. 2002; MajsaK et al., 1998; Morris et al., 1994a,b, 1996; Nowak and Hermsdorfer, 2006). However, subjects with Parkinson’s disease showed no notable increase in their self-determined maximal speed of reach and grasp of a stationary ball even after reaching much more quickly to grasp a moving ball or a stationary ball that was available for grasp for only a brief time. Thus, a transfer of reaching speed from one task context to another did not occur. It is possible that additional trials may have resulted in transfer to the stationary ball condition. However, the motor behavior of individuals with Parkinson’s disease appears to be stimulus contingent. Thus an important clinical implication is that although individuals with Parkinson’s disease may improve their motor output in one task context, it cannot be assumed that their improved motor skill will transfer to other tasks or affect all deficits equally.

References


