

# Lateral Stepping for Postural Correction in Parkinson's Disease

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**ABSTRACT.** King LA, Horak FB. Lateral stepping for postural correction in Parkinson's disease. *Arch Phys Med Rehabil* 2008;89:492-9.

**Objective:** To characterize the lateral stepping strategies for postural correction in patients with Parkinson's disease (PD) and the effect of their anti-parkinson medication.

**Design:** Observational study.

**Setting:** Outpatient neuroscience laboratory.

**Participants:** Thirteen participants with idiopathic PD in their on (PD on) and off (PD off) levodopa state and 14 healthy elderly controls.

**Interventions:** Movable platform with lateral translations of 12cm at 14.6cm/s ramp velocity.

**Main Outcome Measures:** The incidence and characteristics of 3 postural strategies were observed: lateral side-step, crossover step, or no step. Corrective stepping was characterized by latency to step after perturbation onset, step velocity, and step length and presence of an anticipatory postural adjustment (APA). Additionally, percentages of trials resulting in falls were identified for each group.

**Results:** Whereas elderly control participants never fell, PD participants fell in 24% and 35% of trials in the on and off medication states, respectively. Both PD and control participants most often used a lateral side-step strategy; 70% (control), 67% (PD off), and 73% (PD on) of all trials, respectively. PD participants fell most often when using a crossover strategy (75% of all crossover trials) or no-step strategy (100% of all no-step trials). In the off medication state, PD participants' lateral stepping strategies were initiated later than controls ( $370 \pm 37\text{ms}$  vs  $280 \pm 10\text{ms}$ ,  $P < .01$ ), and steps were smaller ( $254 \pm 20\text{mm}$  vs  $357 \pm 17\text{mm}$ ,  $P < .01$ ) and slower ( $0.99 \pm 0.08\text{m/s}$  vs  $1.20 \pm 0.07\text{m/s}$ ,  $P < .05$ ). No differences were found between the PD off versus PD on state in the corrective stepping characteristics. Unlike control participants, PD participants often (56% of side-step strategy trials) failed to activate an APA before stepping, although their APAs, when present, were of similar latency and magnitude as for control participants. Levodopa on or off state did not significantly affect falls, APAs, or lateral step latency, velocity, or amplitude ( $P > .05$ ).

**Conclusions:** PD participants showed significantly more postural instability and falls than age-matched controls when stepping was required for postural correction in response to lateral disequilibrium. Although PD participants usually used a similar lateral stepping strategy as controls in response to lateral translations, lack of an anticipatory lateral weight shift, and bradykinetic characteristics of the stepping responses help

explain the greater rate of falls in participants with PD. Differences were not found between the levodopa on and off states. The results suggest that rehabilitation aimed at improving lateral stability in PD should include facilitating APAs before a lateral side-stepping strategy with faster and larger steps to recover equilibrium.

**Key Words:** Accidental falls; Parkinson's disease; Posture; Rehabilitation.

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**F**ALLS AMONG PEOPLE with Parkinson's disease (PD) are a major problem. One study recently determined the frequency of falls in a group of 350 ambulatory people with PD. It was reported that 46% of people with PD fell at least once a week and 33% fell at least 2 or more times a week.<sup>1</sup> In fact, PD patients had a 9-fold increased risk of sustaining recurrent falls when compared with age-matched people without PD.<sup>2</sup> Inadequate postural responses in response to external perturbations contribute to frequent falls in PD.<sup>3,4</sup> Most of what is understood regarding postural reactions in patients with PD is based on responses to perturbations in the anteroposterior direction. Automatic postural responses in PD have normal latencies but reduced magnitudes (bradykinesia) for both feet in-place and stepping responses.<sup>3,5</sup> Forward stepping responses are also significantly shorter than normal with small anticipatory postural adjustments (APAs).<sup>6</sup>

PD participants may be even more unstable in the lateral than in the forward direction. Previous studies have shown reduced lateral stability in PD patients as assessed by reduced "stability boundaries" or how far PD participants can voluntarily lean during quiet stance.<sup>7</sup> Additionally, it was found that PD participants had an increase in mediolateral postural sway during quiet stance when compared with age-matched controls.<sup>8</sup> Postural responses to small, lateral perturbations with the feet in place are also smaller than normal in patients with PD.<sup>4</sup> We found no previous studies that have examined compensatory stepping responses to fast, large lateral perturbations in patients with PD.

Younger subjects, in response to fast large platform perturbations, have been found to favor a single crossover strategy with the limb that was initially unloaded whereas older subjects frequently used a side-stepping strategy with multiple steps that more often resulted in limb collision.<sup>9,10</sup> Side-stepping requires an APA, involving an increase of vertical force under the leg that will step in order to unload it quickly.<sup>11</sup> It is unknown whether patients with PD use the same crossover and lateral stepping strategies as healthy people in response to lateral perturbation. Besides strategy selection problems, lateral instability in PD may result from smaller or later stepping responses or from missing or ineffectual APAs in preparation for lateral stepping.

The object of this study was to characterize the lateral stepping strategies used by participants with PD and the effects of anti-parkinson medication compared with age-matched controls. We hypothesized that PD participants would more often use a crossover strategy because of their difficulty generating

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an APA to shift their weight off of the leg loaded by the postural perturbation to side step.<sup>12,13</sup> We also predicted that APAs, if present, would be smaller than normal, that there would be a greater number of falls for the PD group, and that the levodopa on state would improve compensatory stepping and reduce falls in the PD participants.

## METHODS

### Participants

Fourteen healthy, elderly controls and 13 patients with idiopathic PD were included in this study. We recruited participants from the Department of Neurology, Oregon Health Sciences University (OHSU). PD and control participants who had other causes of balance impairment, including somatosensory, visual, vestibular, or orthopedic impairment were excluded. PD subjects with significant postural tremor, dystonia, or dementia were excluded. All PD subjects had moderate to severe PD with significant balance problems. Control participants were healthy, ambulatory people recruited from the community. Table 1 summarizes the PD participants' age, sex, duration of PD, clinical scores, and percentage of fall trials during the experiment. The control group included 12 men and 2 women. The PD group consisted of 9 men and 4 women. There were no significant differences between the groups for age, weight, or height. The average age for the controls was  $62 \pm 2$  years and  $63 \pm 2$  years for the PD group. The average weight for the PD group was  $73.6 \pm 5.5$ kg, and  $79.5 \pm 4.1$ kg for the controls. The average height for the PD group was  $170.2 \pm 2.5$ cm ( $67 \pm 1$ in) and  $175.3 \pm 2.5$ cm ( $69 \pm 1$ in) for the controls. All participants gave informed consent for protocols approved by the Institutional Review Board of OHSU.

### Experimental Protocol

All PD participants were tested at 8:00 AM in the off state, after at least 12 hours since their last dose of dopamine replacement therapy. They were then tested in the on state later that same day (at least 45min after taking their medication). Immediately before each set of experiments, participants were tested on the motor subsection III of the United Parkinson's Disease Rating Scale (UPDRS)<sup>14</sup> and the modified Hoehn and Yahr stages.<sup>15</sup>

All participants stood on dual forceplates on a moveable platform looking straight ahead, with arms at their side and feet

in narrow stance, in order to facilitate a step. Narrow stance was defined as feet 4.5cm apart, both at the calcaneus and great toe, so that their feet were parallel. Participants wore a harness attached to the ceiling without any tension and an assistant stood behind them for safety. Before platform translation, the participants were instructed to have equal weight distribution between their right and left feet and this was monitored by an oscilloscope. Participants were instructed to keep their balance as best they could. Each participant had 7 trials consisting of 12cm lateral platform translations at 14.6cm/s ramp velocity. The mean average peak acceleration and deceleration were  $1284 \pm 80.5$  and  $547 \pm 40.55$ cm/s<sup>2</sup>, respectively. Figure 1 contains the velocity, acceleration, and deceleration profile. The direction of platform translation was toward the less involved side such that participants fell or stepped toward their more involved side. The more involved side was determined by the motor components of the UPDRS, which included the bilateral assessment of tremor at rest and with action, rigidity, finger taps, hand movements, rapid alternating movements, and leg agility. The direction of platform translation for the control participants was randomized.

### Data Collection and Analysis

Video recordings from both the back and side of the participants were used to determine the postural strategies used for each of the 7 trials. We identified 3 separate strategies: side-step, crossover, and no-step. Side-step was defined as lifting the initially weighted leg, opposite the direction of platform translation, thereby widening the base of support. This side-step strategy requires active unloading of the weighted leg before stepping.<sup>9,11</sup> The crossover strategy involved lifting of the leg unweighted by motion of the platform and crossing that leg over the stance leg.<sup>11</sup> The no-step strategy was defined as an inverted pendulum "timber-like" response, without lifting either leg. For each participant, the percentage of 7 trials in which each strategy was used was calculated and a group mean percent incidence was determined.

We also used the videotapes to verify falls. Falls were defined as trials in which the assistant performed a hands-on assistance or the participants were caught by the harness before their knees hit the floor. The research assistant was experienced and did not assist any participant until a fall was inevitable, knowing that the harness would prevent them from actually

Table 1: Characteristics of Participants With PD

Participant	Age (y)	Sex	Years of PD	Hoehn and Yahr Stages	UPDRS Score off Levodopa	UPDRS Score on Levodopa	Percentage Falls off Levodopa	Percentage Falls on Levodopa
1	65	M	12	4	81	44	0	29
2	69	M	16	3	72	63	100	100
3	64	M	9	4	57	20	0	0
4	60	M	11	3	53	16	0	0
5	71	M	11	3	49	39	43	14
6	65	M	21	2	49	38	0	0
7	66	M	5	3	44	32	0	0
8	56	F	14	3	44	5	0	0
9	53	M	13	4	42	13	56	15
10	39	F	15	3	40	6	57	57
11	67	F	3	4	32	30	100	100
12	58	M	28	3	21	11	100	0
13	76	F	3	2	21	11	0	0

Abbreviations: F, female; M, male; UPDRS, United Parkinson's Disease Rating Scale.

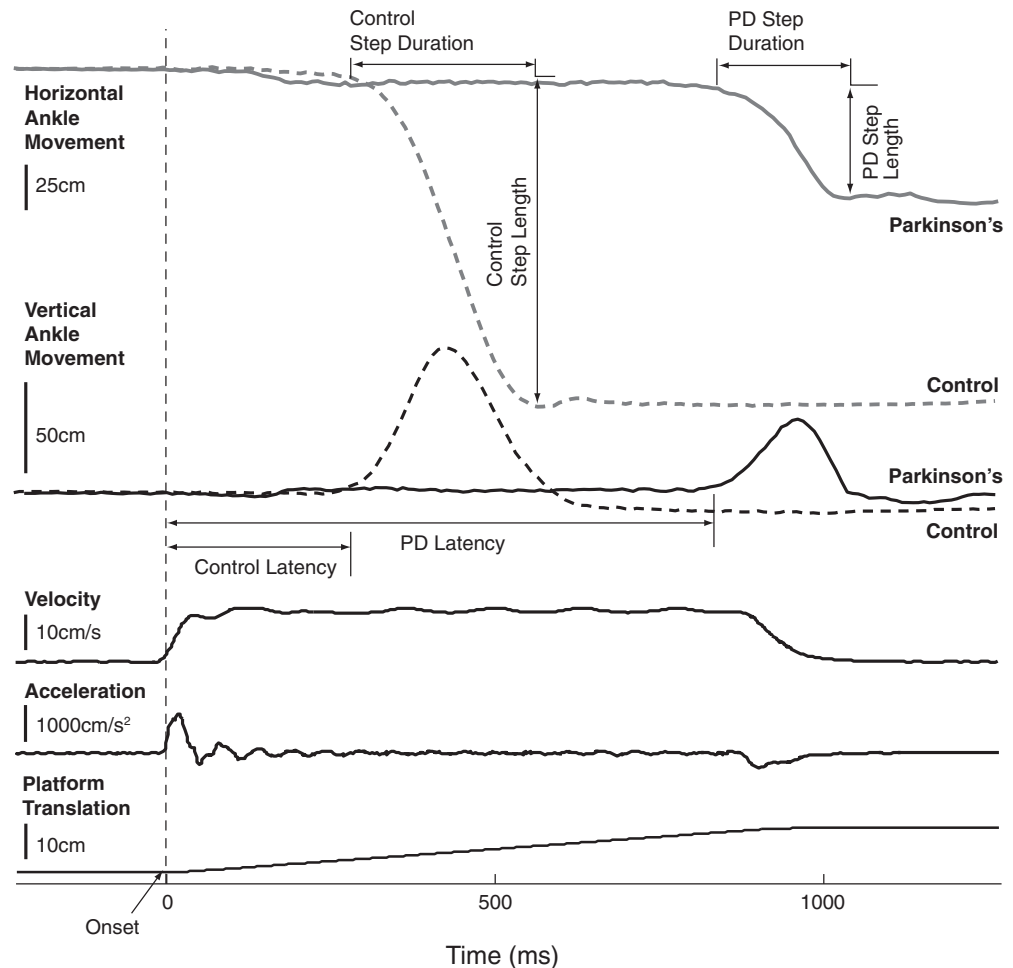


Fig 1. Example of kinematic ankle marker displacement used to determine parameters of step latency, step length, and step duration. Step duration ( $D$ ) was used to calculate step velocity ( $V$ ) ( $V=L/D$ ). Velocity and acceleration lines indicate movement of platform.

falling to the floor. The percentage of trials that resulted in a fall was calculated for each strategy type for each participant.

Parameters of the side-step strategy were quantified with step length, step velocity, and step latency using ankle marker kinematics and Matlab software.<sup>a</sup> It was not possible to quantify these variables in the crossover and no-step strategies because of difficulty identifying ankle markers and because so many PD participants fell when using these strategies. A high-resolution Motion Analysis system<sup>b</sup> with 6 video cameras recording at 60Hz provided a 3-dimensional representation of leg and body movement from a reflective marker on the lateral malleolus of the stepping foot. A reflective marker on the moving platform was used to subtract translation of the platform from the body markers to measure step length. Step velocity was calculated by dividing step length by step duration. Step latency was determined from the time of surface translation to first detectable vertical motion of the lateral malleolus marker of the stepping foot compared with background, stationary stance. Figure 1 shows the platform and ankle marker movements in the vertical and horizontal directions. For this figure, we chose the participant (participant 9) with the longest latency in order to more clearly display how we measured the differences between control and PD participants.

We defined APAs as a lateral weight shift that occurred before the participant lifted their foot off the forceplate and at

least 50ms after the onset of a perturbation. APAs were characterized by an increase in vertical surface reactive force under the leg that was about to step.<sup>11</sup> The peak magnitude and onset latencies of the APAs were calculated using Matlab software. Latency of APA was chosen as the moment when the difference in weight loading began to displace from its background level and the APA peaks were chosen as the maximal displacement of the participants' weight on a given trial (fig 2).

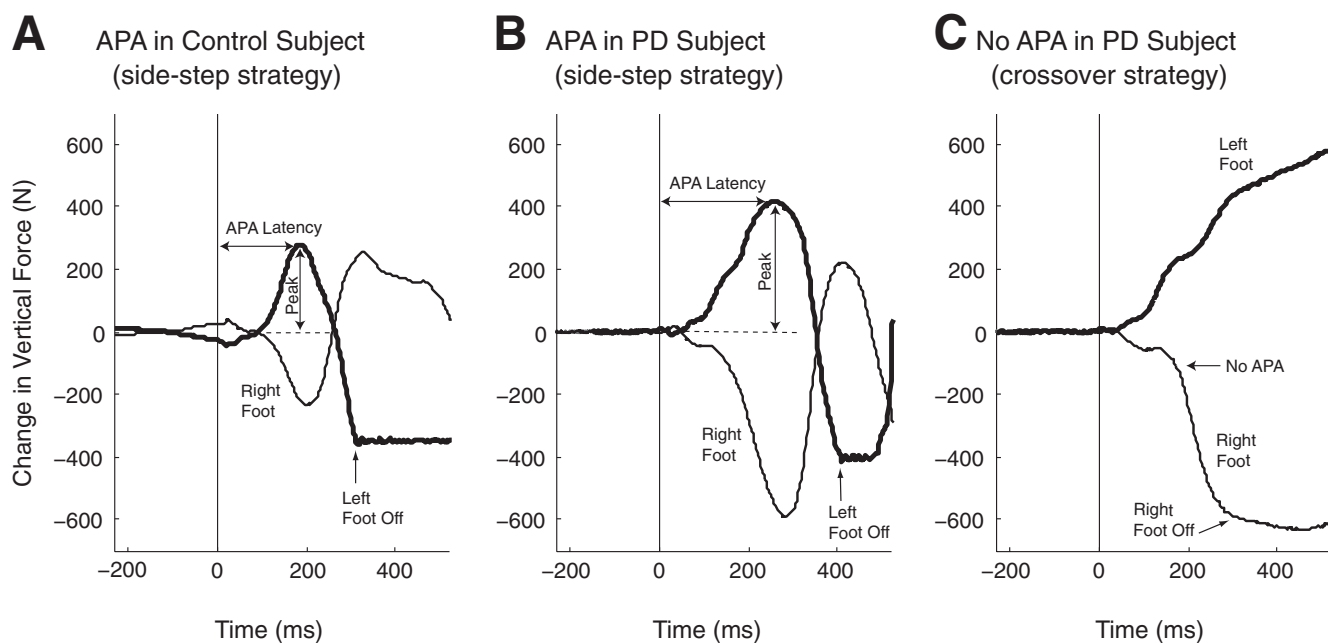
### Statistical Analysis

Except for the step velocity variable, nonparametric statistical tests were used because the data were not normally distributed (Shapiro-Wilk test). Comparisons between the PD on or off state versus controls were tested using the Mann-Whitney  $U$  test and the  $t$  test. Comparisons between the PD on versus PD off state were tested with the Wilcoxon  $T$  and paired  $t$  tests. To assess the relationship between variables, Pearson and Spearman correlation coefficients were calculated.

## RESULTS

### PD Participants Fell More Often Than Controls

Table 1 summarizes the results of fall trials in the PD participants, both in the off and on medication state. Three PD participants in the off state fell in every trial, 3 fell in some, but



**Fig 2.** Examples of vertical ground reaction force measures associated with lateral stepping responses. (A) Control participant side-stepping with APA. (B) Participant (participant 4, off medication) side-stepping with APA. Although, when present, the average size of the APAs was the same among groups, in this example the PD participant has a larger APA than the control and has a later onset of stepping. (C) Participant (participant 4, off medication) using crossover step with no APA.

not all trials, and 7 participants never fell. In the PD on state, 2 participants fell in every trial, 4 fell in some of the trials, and 7 participants never fell. The frequency of falls did not correlate with the severity of PD, as determined by their UPDRS motor score (Spearman  $\rho = .13$ ,  $P = .571$ ). The PD participants fell more often than the controls, regardless of medication state (Mann-Whitney  $U$ ,  $z = -2.57$ ,  $P = .046$ ) (table 2). Specifically, only 1% of all trials in control participants ended in falls, because only 1 control participant fell on one of 7 trials. In contrast, 35% of trials for participants in the PD off state and 24% of trials in the PD on state ended in falls. There was no significant difference in number of falls for PD participants on versus off medication (Wilcoxon test,  $z = -1.29$ ,  $P = .197$ ).

### PD Participants Used Similar Strategies as Controls But Had More Variability in Their Responses

There were no significant differences in the type and/or incidence of postural response strategies used by the groups in

**Table 2: Group Mean Percentage of Trials Using Each Strategy and Percentage of Trials With Falls**

Strategy	Control	PD off Levodopa	PD on Levodopa
Side-step			
% Trials	70 ± 12	67 ± 13	73 ± 12
% Falls	1 ± 4	17 ± 13	14 ± 10
Crossover			
% Trials	30 ± 12	19 ± 10	15 ± 10
% Falls	0 ± 0	75 ± 15	36 ± 22
No-step			
% Trials	0 ± 0	14 ± 10	12 ± 8
% Falls	0 ± 0	100 ± 0	100 ± 0

NOTE. Values are mean percent ± standard error of the mean (SEM).

response to lateral surface translations. Most participants, regardless of group or medication status, used a lateral side-step, with the limb initially loaded in order to maintain their balance. However, PD participants, in both the on and off medication state, took multiple steps when using the side-step strategy, compared with controls who took a single step to the side. Specifically, 70% of trials in control participants involved 1 step, 22% involved 2 steps, and just 8% involved 3 or more steps. Of the PD group in the off state trials, 41% of trials involved 1 step, 28% involved 2 steps, and 31% involved 3 or more steps to recover their balance. For this group in the on state, 36% of trials involved 1 step, 30% involved 2 and 34% involved 3 or more steps.

The next most common strategy for both groups was to cross over in front of the other foot in response to lateral platform translations. There were no significant differences between the groups in the frequency of this strategy but as discussed below, the fall frequency was higher when PD participants used the crossover strategy. Finally, 2 PD participants in the on and 2 in the off medication state used a no-stepping strategy but no control participants used this strategy for any of their trials.

Control participants consistently had the same postural strategy for all 7 trials. In fact, only 1 participant varied their strategy for one of their trials. Of the 14 controls, 9 people consistently used a side-step and 4 consistently used a crossover. No control ever used the no-step strategy. In contrast to control participants, there was more variation in strategy in the PD group. Two participants in the off state and 1 participant in the on state varied their strategy within the 7 trials and 3 participants varied strategies between the off and on medication state. In the on state, 1 participant varied the strategy with the majority of the trials resulting in no steps. Of the PD participants who changed strategies either within trials or between the off and

on state, there was a high rate of falls; 57% to 100% of the time.

### PD Participants Used Strategies That Were Often Not Successful

Table 2 summarizes the incidence of the 3 strategies: side-step, crossover, and no-step. The data show that most people used a side step in order to maintain their balance (70% control, 67% PD on, 73% PD off). The percentage of falls for each strategy shows the success of the strategy. We found that the side-stepping strategy produced the least number of falls regardless of the group (see table 2). Four control participants used the crossover strategy (30% of all control trials) consistently and never fell. In contrast, the PD participants often fell when using the crossover strategy. In the off state, the 3 PD participants who used the crossover strategy (19% of all trials) fell at high rates (75% of crossover trials). PD participants on medication crossed over on 15% of the trials and fell in 36% of these crossover trials. We quantified limb collision in those crossover trials and found that in the control group, there were no incidents of limb collision. In the PD crossover trials, those participants in the off state had 28% of trials associated with limb collision and in the on state, only 7%. For the PD participants, the limb collision occurred when the participant did not lift their foot high enough to clear the stance leg.

As summarized in table 2, no control participants used a no-stepping strategy and of the PD participants who had this strategy, they fell 100% of the time, whether they were on or off medication.

### PD Participants Had Longer Latencies, Shorter Steps, and Slower Step Velocity

We found significant differences between controls and PD groups, regardless of the medication state, but not between PD off and PD on states for step latency, step length, and step velocity. Figure 1 shows an example of the vertical and horizontal ankle motion during lateral side stepping in response to platform translations for a control and PD participant. It shows a later, smaller and slower step in the PD than in the control participant. The step latency for the PD group in the off state ( $370 \pm 37$ ms) was significantly different from controls ( $280 \pm 10$ ms) as determined by the Mann-Whitney *U* test ( $z = -2.31$ ,  $P = .021$ ). These participants in the on state ( $359 \pm 30$ ms) also differed significantly from controls (Mann-Whitney *U*,  $z = -2.22$ ,  $P = .027$ ). There was no difference between PD off and on states for latency of stepping (Wilcoxon,  $z = -.420$ ,  $P = .674$ ). Step latency was positively correlated with falls (Spearman  $\rho = .56$ ,  $P = .005$ ) and step latency was correlated with step length (Spearman  $\rho = -.51$ ,  $P = .009$ ), however, severity of disease, as measured by the UPDRS motor score, did not correlate with any step characteristics.

Significant differences were also found for step length between PD in the off state ( $254 \pm 26$ mm) and controls ( $357 \pm 17$ mm) as determined by Mann-Whitney *U* ( $z = -2.89$ ,  $P = .004$ ) and for PD in the on state ( $234 \pm 33$ mm) versus controls ( $z = -2.80$ ,  $P = .005$ ). No difference existed in step length between the PD off and PD on states (Wilcoxon,  $z = -1.26$ ,  $P = .208$ ). Step velocity also showed significant differences between the PD off state ( $.99 \pm .08$ m/s) and controls ( $1.20 \pm 0.07$ m/s) as measured by independent *t* test ( $t_{15} = 2.19$ ,  $P = .044$ ), and also between the PD on state ( $.92 \pm .01$ m/s) and controls ( $t_{15} = 2.24$ ,  $P = .041$ ). There was no difference for the PD groups between their off and on states, as measured using a paired *t* test ( $t_7 = .49$ ,  $P = .645$ ). See figure 3 for these results.

To determine the effects of adaptation over the course of 7 trials, we also compared step length, velocity, and latency between the first versus the last trials. We found no significant difference between the first and last trial in either of the groups except step length in the PD group, on state (Wilcoxon,  $P = .02$ ), in which the step length was significantly longer in the last, versus the first, trial.

### APAs Were Often Absent in PD Participants

The control participants were very consistent within their 7 trials, with side-stepping strategy always preceded by an APA and with the crossover strategy never associated with an APA, with only 1 exception. In the 30% of control participants' trials with crossover stepping, only 1 participant used an APA and it was consistent in all 7 trials. This APA was under the foot that crossed over such that they assisted the unloading of that leg from the perturbation. The peak and latency of the APAs during side-stepping are shown in table 3.

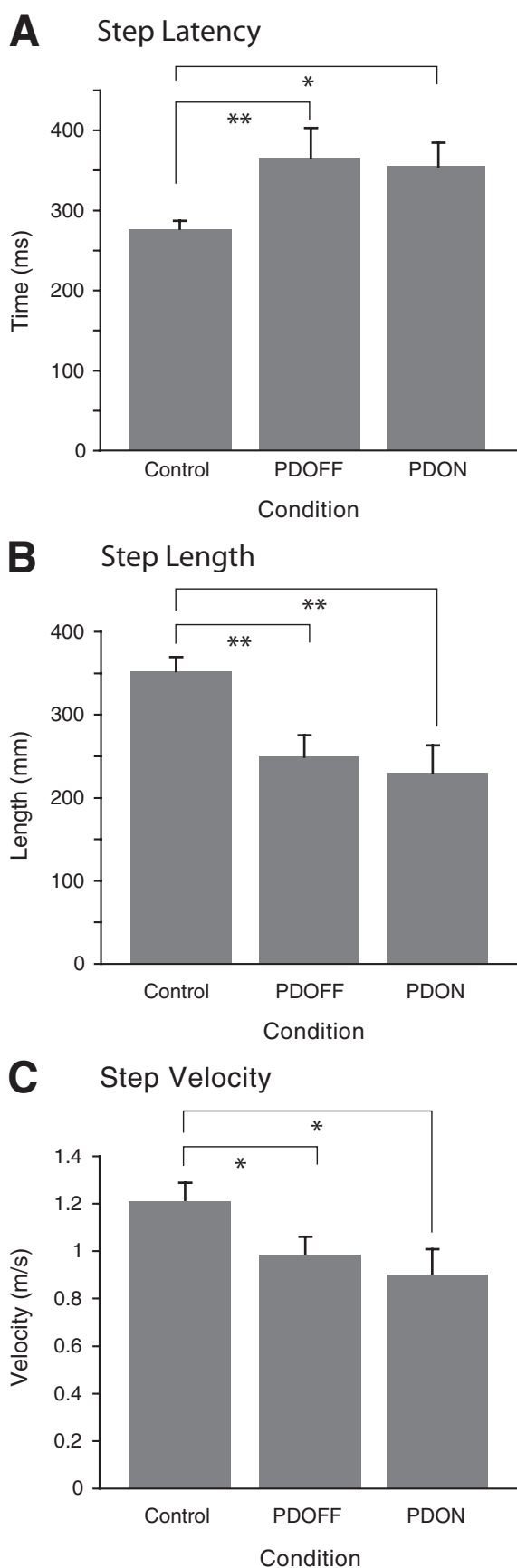
Unlike controls, PD participants, in the off state, used an APA in only 56% of their side-stepping trials. Of these PD participants who had an APA, 2 used it consistently for all 7 trials and the other 4 varied in the use of an APA with side-stepping and/or crossover. The size and the latency of the APAs, when used by PD participants in the off state when side-stepping, did not differ statistically ( $P = .08$  for both peak and latency of the APAs) from controls despite the fact that their steps were later (see table 3).

Levodopa on or off status did not change the incidence of the APAs before the side-stepping strategy (see table 3). Four PD participants in the on state never side-stepped and never used an APA. Two of the 6 PD participants in the on state who used an APA in side-stepping were consistent in all 7 trials. The other 4 PD participants in the on state varied in use of APA for side-stepping. Levodopa did not change the peaks or latencies of the APAs for side-stepping ( $P = .84$ ,  $P = .86$  respectively). All PD participants, on and off, who fell without taking any steps, never used an APA.

## DISCUSSION

PD participants showed significantly more postural instability and falls than age-matched control participants when stepping was required for postural correction in response to lateral disequilibrium. The results of our study show that although PD participants usually used the same side-stepping postural strategy as age-matched control participants in response to lateral translations, there were significant differences in the characteristics of the stepping responses that help explain the greater rate of falls associated with PD. The results did not support our hypothesis that PD would affect strategy selection, as expected from other studies.<sup>16,17</sup> Specifically, we expected PD participants to use a crossover strategy more often than control participants because of their difficulty in generating sufficient force for anticipatory, lateral postural adjustments necessary for step initiation.<sup>12,18</sup> Instead, we found that relative use of the lateral step and crossover strategies did not differ between PD and elderly control participants. Some participants with PD used the no-step strategy; however, none of the control participants did. When present, the APAs in participants with PD had sufficient force and latency, although their steps occurred at a longer latency and lower velocity. In fact, when PD participants did use the crossover strategy, they usually fell, unlike controls who almost never fell.

In terms of strategy success, side-stepping was associated with the least number of falls for PD participants. This suggests that side-stepping is the safest and most effective response for



people with PD, when the perturbation occurs during double supported, quiet stance. Unlike participants with PD, 4 of 13 older control participants successfully used a crossover strategy, which was never associated with falling. This crossover strategy requires the ability to maintain postural equilibrium with narrow stance, joint flexibility that affords stable placement of both feet on the floor in a crossover stance, and fast leg movements. Although the elderly controls who used the crossover strategy never fell, the PD participants who used the crossover strategy fell in 75% of trials in the off state and in 36% of trials in the on state. Therefore, PD participants often used a strategy that was ineffective for them. The higher rate of falls in PD than control participants suggest either a poor strategy selection or a sensorimotor inability to effectively execute the strategy.

Consistent with our initial hypothesis that PD participants have difficulty selecting appropriate postural strategies is their relative inconsistency in terms of which strategy was evoked by the lateral translations. Whereas each control participant consistently used either the lateral-step or crossover strategy, many PD participants used different strategies across their 7 trials or when in the on versus off state. Those PD participants who had varying strategies also had the highest fall rates. Thus, an inability to preselect a consistent response to a perturbation may delay execution and result in more falls. In fact, a recent study from our laboratory showed that when healthy young participants cannot preplan which foot to select for stepping forward in response to surface translation, they also show delayed onset of step initiation despite normal onset of APAs before the steps.<sup>19</sup>

Falls in PD participants associated with the most common, and most appropriate strategy, side-stepping, were associated with the longest latencies to get the foot off the ground while the body center of mass (COM) was falling over its base of foot support. Long latencies of postural responses to external perturbations have not been observed previously in PD. In fact, feet-in-place responses to surface translations have normal electromyographic activity, reactive force, and kinematic latencies except for earlier than normal muscle antagonist responses.<sup>3,5</sup> We had anticipated that the delayed latencies to lifting the stepping foot off the ground when using the lateral stepping strategy in PD participants were probably due to later and smaller than normal APAs under the step leg, which is weighted by the movement of the body COM over it during the translation. However, we found that this was not the case. In fact, 6 of the 7 PD participants in the off state that never fell using a side-stepping strategy had a normal size and latency of their APAs on the majority of trials. In contrast, the 3 PD off participants that fell in every trial never used an APA, whether they "timber fell" without a step or attempted to crossover or attempted to use a side-stepping strategy. The same relationship held true for PD participants in the on state; of the 5 participants who never fell, all 5 of these participants had normal APAs on the majority of all trials. This suggests an important relationship between the use of an APA involving an active push down by the stepping leg and successful recovery from a lateral translation.

**Fig 3. Characteristics of side-stepping; comparisons of step latency, step length, and step velocity, with standard error bars. (A) The histogram for step latency illustrates the time from lateral platform translation to initiation of a side-step to maintain balance for control, PD off, and PD on groups. (B) The histogram for step length compares the length of the side-step among the control, PD off, and PD on groups. (C) The histogram for velocity of side-step compares the velocity of the side-step among the control, PD off, and PD on groups. \* $P > .05$ ; \*\* $P > .01$ .**

**Table 3: APA Incidence, Size, and Latency in Side-Stepping Strategy**

APA	Controls	PD off Levodopa	PD on Levodopa
% trials with APA	100	56	62
Peak of APA (N)	311±13	351±14	306±18
Latency of APA (ms)	229±5	244±8	237±12

NOTE. Values are percent or mean ± SEM.

It is surprising that in many trials, PD participants showed normal size and latency of APAs despite having slow stepping latencies. These results suggest that different circuits may be responsible for APA generation versus actual postural stepping. There is evidence for cortical involvement in APAs before voluntary stepping, specifically the supplementary motor cortex.<sup>20</sup> In contrast, the brainstem pedunculopontine nucleus (PPN) is known to be associated with initiating stepping movements with stimulation<sup>21,22</sup> and akinesia with bilateral lesioning.<sup>23</sup> Both of these areas, the supplementary motor cortex, and the PPN, are known to be affected by PD<sup>24</sup> and it may be that PD participants with varying degrees of involvement in these areas would have different anticipatory postural or step triggering difficulties. For example, the nonfallers in our study had later step latencies, although their postural APA appeared intact, consistent with intact supplementary motor cortex but impaired triggering of step initiation via PPN. In contrast, the fallers had problems generating any APA resulting in timber and crossover falls, consistent with impaired supplementary motor cortex.

Unlike voluntary step initiation, lateral compensatory stepping did not improve significantly with levodopa anti-parkinsonian medication.<sup>3</sup> Levodopa on versus off status did not change strategy, stepping characteristics or number of falls or use of the APA, suggesting that levodopa does not improve compensatory stepping as it does voluntary stepping. This difference in effects of levodopa replacement medication between self-initiated and externally triggered step initiation suggests different central neural circuits for these 2 stepping behaviors that show so much resemblance.<sup>3,12,25</sup> The lack of improvement in lateral stepping responses for balance correction with anti-parkinsonian medication is, however, consistent with previous studies showing lack of improvement of feet-in-place postural responses to backward surface translations.<sup>3</sup> The lack of improvement in reactive balance control with levodopa replacement is also consistent with the incidence of falls in the levodopa on state compared with the levodopa off state in PD.<sup>26</sup>

### Study Limitations

One limitation of our study was that we were not able to analyze the kinetic parameters of the crossover strategy due to the high number of falls and difficulty seeing markers. In the 3 PD participants for whom we could measure the latency to step initiation when using a crossover strategy, the latencies were more than double their latencies for side-stepping. These long latencies to step initiation and lack of an APA when using the crossover strategy suggests that the stepping limb was lifted passively as it was unloaded by the platform translation as the body fell laterally. In contrast, studies have shown that the crossover strategy in healthy elderly has a shorter latency to step initiation than a side-stepping strategy, which requires active unloading before leg lifting.<sup>11</sup> In some trials, PD participants appeared to first select a lateral step but it was very small and ineffective, and was then followed by a crossover step and fall. Thus, the frequent falls associated with the crossover

strategy in PD participants, but not in controls, may be due to poor strategy selection, inability to generate an APA to side step, and/or to bradykinetic initiation and execution of the step.

The slow, late, small stepping associated with the PD participants' most successful strategy of side-stepping is consistent with bradykinetic postural responses reported previously.<sup>3</sup> When PD participants did not step at all, this likely represented a failure to evoke any stepping strategy, similar to freezing of voluntary step initiation, something that the controls never did because the perturbation was too fast and large to maintain equilibrium with an in-place postural response, with narrow stance.

Because our latencies to stepping were based on initial kinematic change in foot position, rather than on electromyographic activity or ground reaction forces, they are considerably late. Our latencies to step initiation of 300ms in control participants would be consistent with postural electromyographic responses of 100 to 150ms plus 50ms electromechanical delay, plus another 150ms delay between initial ground reaction force and kinematic detection of foot motion.<sup>27</sup> It is unlikely that the deceleration of the platform influenced stepping response because the stepping occurred before the deceleration peak at 1000ms.

The reasons for strategy failure are important to understand when developing a rehabilitation program to focus balance training on a patient's primary balance constraints.<sup>28</sup> Our results indicate that clinicians may need to consider 2 different strategies for training lateral stepping for balance, one that focuses on step latency and size (for those participants who side step) or on lateral weight shifting (for those participants who lack an APA and so timber-fall or crossover and fall). Because falls had a strong correlation with both delayed step latency and to absent APAs, both requirements for successful compensatory stepping should be considered, perhaps separately, by the therapist.

Because lateral side-stepping was the most successful strategy, therapists should reinforce this strategy (as well as compensatory grasping) to help prevent falls in response to lateral perturbations from a standing posture. However, falls also occur during gait and different lateral postural strategies may be required to recover lateral stability during gait. For example, it may be more advantageous to use a crossover strategy if a person is already unloaded in mid-swing. However, therapists need to be aware that the crossover strategy is inherently more unstable because effective torques for moving the body COM over 1 leg are small and because the final base of support is very narrow. Nevertheless, studies have shown that mediolateral stepping was modifiable and that training of compensatory stepping effectively increased step length, shortened step latency, and increased step speed and carried over to voluntary gait parameters in patients with PD.<sup>29-31</sup> Future studies should include consideration of these different strategies in varying phases of the gait cycle.

### CONCLUSIONS

Impaired lateral compensatory stepping strategies in PD can lead to falls and are not improved in the on state of dopamine replacement medication. Therapy programs aimed at improving lateral stability in PD should include a lateral stepping strategy with faster and larger steps as well as facilitating lateral weight shifts.

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## Suppliers

- a. The MathWorks Inc, Apple Hill Dr, Natick, MA 01760-2098.
- b. Motion Analysis Corp, 3617 Westwind Blvd, Santa Rosa, CA 95403.