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Lateral Stepping for Postural Correction in Parkinson's Disease

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Abstract

OBJECTIVES—Effective balance rehabilitation requires an understanding of how patients with balance disorders attempt to recover equilibrium in response to external perturbations. The objective of this study is to characterize, for the first time, the lateral stepping strategies for postural correction in patients with Parkinson's Disease (PD) and the effect of their antiparkinson medication.

DESIGN—Observational study.

SETTING—Outpatient neuroscience laboratory.

PATIENTS—Thirteen subjects with idiopathic Parkinson's disease (PD) in their ON and OFF levodopa state (PD ON and PD OFF) and 14 healthy elderly controls.

INTERVENTIONS—Movable platform with lateral translations of 12 cm at 55cm/s ramp velocity.

MAIN OUTCOME MEASUREMENTS—The incidence and characteristics of 3 postural strategies were observed: lateral step (the limb loaded by the perturbation was unloaded and lateral base widened), cross-over step (the limb unloaded by the perturbation stepped over the front of the other foot) or no step (usually associated with a 'timber' fall). Corrective stepping was characterized by latency to step after perturbation onset, step velocity and step length. Additionally, percentages of trials resulting in falls were identified for each group.

RESULTS—Whereas elderly control subjects never fell, PD subjects fell in 27% and 36% of trials in the ON and OFF states, respectively. Both PD and control subjects most often used a lateral step strategy; 70% (control), 64% (PD OFF) and 73% (PD ON) of all trials, respectively. PD subjects fell most often when using a cross-over strategy (75% of all cross-over trials) or no-step strategy (100% of all no-step trials). PD OFF subject's lateral stepping strategies were initiated later than controls (370 ± 37 vs. 280 ± 10 ms; $p < .01$), and steps were smaller (254 ± 20 vs. 357 ± 17 cm; $p < .01$) and slower (0.99 ± 0.08 vs. 1.2 ± 0.07 cm/sec; $p < .05$). No differences were found between PD OFF versus PD ON in the corrective stepping characteristics. Late steps were associated with falls with a correlation of 0.79, $p > 0.01$. Levodopa medication did not significantly affect falls, lateral step latency, velocity or amplitude ($P > .05$).

CONCLUSIONS—PD subjects showed significantly more postural instability and falls than age-matched control subjects when stepping was required for postural correction in response to lateral disequilibrium. Although PD subjects usually chose the same lateral stepping strategy as age-matched control subjects in response to lateral translations, bradykinetic characteristics of the stepping responses help explain the greater rate of falls in subjects with PD. Unlike control subjects, PD subjects were unable to maintain equilibrium when using a cross-over strategy and sometimes failed to take a step at all and fell. Levodopa replacement therapy did not change either strategy selection, stepping characteristics or number of falls, suggesting that levodopa does not improve lateral stepping responses, similar to in-place postural responses. Rehabilitation aimed at improving lateral stability

in PD should encourage a lateral side-stepping strategy with faster and larger steps to recover equilibrium.

Keywords

Postural control; Parkinson's disease; lateral stepping

Introduction

Falls 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. They reported that 46% of people with PD fell at least one time per week and 33% fell at least 2 or more times per week.¹ In fact, PD patients had a 9-fold increased risk of sustaining recurrent falls when compared to age matched people without PD.² Inadequate postural responses in response to external perturbations contribute to frequent falls in PD.³ and 4 Most of what is understood regarding postural reactions in patients with PD is based on responses to perturbations in the anterior-posterior direction. Automatic postural responses in PD have normal latencies but reduced magnitudes (bradykinesia) for both feet in-place and stepping responses.³ and 5 Forward stepping responses are also significantly shorter than normal with small anticipatory postural adjustments.⁶

PD subjects may be even more unstable in the lateral, than the forward, direction. Previous studies have shown reduced lateral stability in PD patients as assessed by reduced 'stability boundaries' or how far PD subjects can voluntarily lean during quiet stance.⁷ Additionally, it was found that PD subjects had an increase in mediolateral postural sway during quiet stance when compared to age matched controls.⁸ Postural responses to small, lateral perturbations with the feet in place are also smaller than normal in patients with PD.⁴ We also found that PD subjects had smaller than normal postural stability margins, measured at the difference between peak center of pressure and peak center of mass displacement, in all directions but most pronounced in the posterior and lateral directions.⁴ However, no previous studies have examined compensatory stepping responses to fast, large lateral perturbations in patients with PD.

If a lateral perturbation to balance is too fast or large to allow postural correction with the feet in place, the subject must expand their base of support such that the center of mass (CoM) is contained within the boundaries of the base. There is more than one way to expand the base of support laterally. For example, when a rightward support surface translation occurs, moving the body CoM to the left with respect to the feet, the left foot is initially loaded and the right foot unloaded. To maintain balance, that person could either sidestep with the left foot, after shifting weight to the right, or cross over the left foot with the right, unloaded foot.⁹ and 10 Either of these strategies could widen the base of support to recover equilibrium between center of mass and base of support (see figure 1).

Previous studies in lateral compensatory stepping have shown that there are age-related changes of strategy choice and characteristics.¹¹ and ¹² Lateral stability and control of the body in the frontal plane is particularly impaired in the elderly, especially in the elderly prone to falls.^{13,14} and ¹⁵ Elderly subjects take more steps to recover their balance, use their arms more and sustain more limb collisions.¹¹ Younger subjects favor a single side step with the limb that was initially loaded while the older subjects used more cross-over strategy with multiple steps that more often result in limb collisions.¹²

The object of this study was to characterize the lateral stepping strategies used by subjects with PD and the effects of antiparkinson medication compared to age-matched control subjects. We

hypothesized that PD subjects would more often use a cross over strategy because of their difficulty with weight shifting from the loaded leg.¹⁶ and ¹⁷ We also predicted that there would be a greater number of falls for the PD group and that levodopa replacement medication would improve compensatory stepping and reduce falls in the PD subjects.

Methods

Subjects

Fourteen healthy, elderly controls and 13 patients with idiopathic PD were included in this study. The control group included 8 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 ± 2 years and for the PD subjects was 63 ± 2 years. The average weight for the PD group was 73.6 ± 5.5 kg, while the controls were 79.5 ± 4.1 kg. The average height for the PD group was 67 ± 1 inches and 69 ± 1 inches for the controls. PD and control subjects with other causes of balance impairment were excluded. Patients with PD who had significant postural tremor, dysmetria, dystonia or dementia were also excluded. Control subjects were healthy, ambulatory subjects recruited from the community. Table 1 summarizes the PD subjects' age, gender, duration of PD, clinical scores and percentage of fall trials during the experiment. All subjects gave informed consent for protocols approved by the Institutional Review Board of Oregon Health Sciences University.

Experimental Protocol

All PD subjects were tested at 8AM 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 afternoon (at least 45 minutes after taking their medication). Immediately before each set of experiments, the subjects were tested on the Motor subsection III of the United Parkinson's disease Rating Scale (UPDRS)¹⁸ and the modified Hoehn and Yahr stages (H&Y).¹⁹

All subjects stood on dual force plates on a moveable platform looking straight ahead, with arms at their side and feet in narrow stance. Narrow stance was defined as feet 4.5 cm apart, both at the calcaneus and great toe such that their feet were parallel. Subjects wore a harness attached to the ceiling without any tension and an assistant stood behind them for safety. Before platform translation, the subjects were instructed to have equal weight distribution between their right and left feet and this was monitored by an oscilloscope. Subjects were instructed to keep their balance as best they could. Each subject had 7 trials consisting of 12 cm lateral platform translations at 55cm/s ramp velocity. The direction of platform translation was toward the less involved side such that subjects 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 controls was randomized.

Data collection and analysis

Video recordings from both the back and side of the subjects were used to determine the postural strategies used for each of the 7 trials. We identified three separate strategies: side-step, cross-over and no-step. Sidestep was defined as lifting the initially weighted leg, opposite the direction of platform translation, thereby widening the base of support. This sidestep strategy requires active unloading of the weighting leg prior to stepping.¹¹ The cross-over strategy involved lifting of the leg unweighted by motion of the platform and crossing that leg over the stance leg.¹¹ The no-step strategy was defined as an inverted pendulum "timber-like" response, without lifting either leg (refer to figure 1). For each subject, the percentage of 7

trials in which each strategy was used was calculated and a group mean percent incidence was determined.

The videotapes were also used to quantify falls. Falls were defined as trials in which the assistant performed a hands-on assistance or the subjects were caught by the harness before their knees hit the floor. The percentage of trials that resulted in a fall was calculated for each strategy type for each subject.

Parameters of the sidestep strategy was quantified with step length, step velocity and step latency using ankle marker kinematics. It was not possible to quantify these variables in the cross-over and no-step strategies because of difficulty identifying ankle markers and because so many PD subjects fell when using these strategies. A high resolution Motion Analysis system (Santa Rosa, CA) with 6 video cameras recording at 60 Hz 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 stepping foot.

Statistics

Except for the step velocity variable, non-parametric statistics were used because the data was not normally distributed (Shapiro-Wilk test). Comparisons between PD ON or OFF versus Controls were tested with independent t-tests (Mann-Whitney U for non-parametrics and Student t-test for parametric). Comparisons between PD ON versus PD OFF were tested with repeated measures t-tests (Wilcoxin T for non-parametric and paired t-tests for parametric). All correlations were tested using Pearson correlations.

Results

PD subjects fell more often than controls

Table 1 summarizes the percent of fall trials in the PD subjects, both in the OFF and ON Medication state. Three PD OFF subjects fell in every trial, 3 fell in some, but not all trials, and 7 subjects never fell. In the PD ON group, 2 subjects fell in every trial, 4 fell in some of the trials, and 7 subjects never fell. The frequency of falls did not correlate with the severity of PD, as determined by their Motor UPDRS score. The PD subjects fell more often than the controls, regardless of medication state ($p < 0.05$; table 1). Specifically, only 1% (± 1) of all trials in control subjects ended in falls. This means that only one control subject fell on one of their seven trials. In contrast, 38% (± 13) of the PD OFF and 27% (± 10) of the PD ON group trials ended in falls. This means that together, 32 of the 84 trials ended in falls for the PD OFF group, while 22 of the 83 trials ended in falls for the PD ON group. There was no significant difference in number of falls for PD subjects ON versus OFF medication.

PD subjects choose similar strategies as controls but had more variability in their choices

There were no significant differences in the type and/or incidence of postural response strategies used by the three groups in response to lateral surface translations. Most subjects in all three groups chose to sidestep laterally, with the limb initially loaded in order to maintain their balance. However, PD subjects, in both the ON and OFF state, took multiple steps when using the sidestep strategy, compared to controls who took a single step to the side. Specifically, 70% of trials in control subjects involved 1 step, 22% involved 2 steps and just 8 % involved 3 or more steps. Of the PD OFF trials, 41% of trials involved 1 step, 28% involved 2 steps and 31 % involved 3 or more steps to recover their balance. For the PD ON group, 36% of trials involved 1 step, 30% involved 2 and 34% involved 3 or greater steps.

The next most common strategy for all groups was to crossover in front of the other foot in response to lateral platform translations. There were no significant differences among the groups in the frequency of this strategy but as discussed below, the fall frequency was higher when PD subjects chose the cross-over strategy. Finally, 2 PD subjects in the ON and 2 in the OFF medication state selected the no-stepping strategy but no control subjects chose this strategy for any of their trials.

Control subjects consistently selected the same postural strategy for all seven trials. In fact, only one subject varied strategy selection for one of their trials. Of the 14 controls, 9 people consistently chose to side step and 4 consistently chose to cross over. No control ever chose the no-step strategy. In contrast to control subjects, there was more variation in strategy selection in the PD groups. Two subjects in the OFF state and one subject in the ON state varied their strategy selection within the seven trials and 3 subjects varied strategy selection between the OFF and ON state. In the ON state, one subject varied their strategy selection with the majority of their trials resulting in no steps. Of the PD subjects who changed strategies either within trials or between the OFF and ON state, there was a high rate of falls; 57 – 100% of the time.

PD subjects choose strategies that were often not successful

Table 2 summarizes the incidence of use of the three strategies; side-step, cross-over and no-step. The data shows that most people, regardless of the experimental group, chose to side step in order to maintain their balance (70%, 64%, 73%). The percentage of falls for each strategy shows the success of the strategy chosen. We found that the sidestepping strategy produced the least number of falls regardless of the experimental group (Table 2). Four control subjects chose the cross over strategy (30% of all control trials) consistently and never fell. In contrast, the PD subjects often fell when attempting to use the cross-over strategy. In the OFF state, the 3 PD subjects who attempted to use the cross over strategy (20% of all trials) fell at high rates (75% of cross-over trials). PD subjects ON medication chose to cross over 15% of the trials and fell in 36% of these cross-over trials. We quantified limb collision in those cross over trials and found that in the control group, there were no incidents of limb collision. In the PD cross-over trials, those subjects in the OFF state, had 28% of trials associated with limb collision and the ON state, only 7%. For the PD subjects, the limb collision occurred when the subject did not lift their foot high enough to clear the stance leg.

As summarized in Table 2, no control subjects chose a no-stepping strategy and of the PD subjects who chose this strategy, they fell 100% of the time, regardless of whether they were ON or OFF medication.

PD subjects had longer latencies, shorter steps and slower step velocity

Figure 2 shows an example of the vertical and horizontal ankle motion during lateral side stepping in response to platform translations for a representative control and PD subject. It shows a later, smaller and slower step in the PD than in the control subject. We found significant differences between controls and PD OFF or PD ON but not between PD OFF and PD ON for step latency, step length and step velocity (see figure 3 for significance values).

Step latency was positively correlated with falls ($r = .79$, $p > 0.01$) and step latency was correlated with step velocity ($r = -.54$, $p < 0.01$) and step length ($r = -.45$, $p < 0.05$). However, severity of disease, as measured by the Motor UPDRS, was not related to any step characteristics.

Discussion

PD subjects showed significantly more postural instability and falls than age-matched controls subjects when stepping was required for postural correction in response to lateral disequilibrium. The results of our study show that although PD subjects usually chose the same postural stepping strategies as age-matched control subjects 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.²⁰ and ²² Specifically, we expected PD subjects to select a cross-over strategy more often than control subjects because of their difficulty in generating sufficient force for lateral postural adjustments necessary for step initiation.¹⁶ and ²³ Instead, we found that relative use of the lateral-step, cross-over and no-step strategies did not differ between PD and elderly controls subjects. In fact, when PD subjects did attempt to use the cross-over strategy, they usually fell, unlike controls who almost never fell.

In terms of strategy success, sidestepping was associated with the least number of falls for PD subjects. This suggests that sidestepping is the safest and most effective response for people with PD. Unlike subjects with PD, 4 out of 13 older control subjects consistently selected a cross over strategy which was never associated with falling. This cross over 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 cross-over stance, and fast leg movements. Although the elderly controls who chose to use the cross-over strategy never fell, the PD subjects who chose the cross-over strategy, fell in 75% of trials in the OFF state and in 36% of trials in the ON state. Therefore, PD subjects often selected a strategy that was ineffective for them. The higher rate of falls in PD than control subjects suggest either a poor decision in strategy selection or a sensorimotor inability to effectively execute the strategy selected.

Choosing to not take a step was not successful for anyone, on any trial. No elderly controls attempted this strategy and when the PD subjects chose this, they fell 100% of the time. This choice may have been a type of 'freezing' rather than a conscious choice not to step.²⁴ Freezing in response to forward falls induced by backward surface translations has recently been shown to be associated with multiple anticipatory postural adjustments, a phenomena not seen in responses to lateral perturbations in our study.²⁵

Consistent with our initial hypothesis that PD subjects have difficulty selecting appropriate postural strategies is their relative inconsistency in strategy selection. Whereas each control subject consistently choose the lateral-step or cross-over strategy, many PD subjects changed strategies across their 7 trials or when in the ON versus OFF state. Those PD subjects who often changed strategies also had the highest fall rates. Thus, an inability to quickly 'decide' how to respond to a perturbation may delay execution and result in more falls.

Falls in PD subjects associated with the most common, and most appropriate strategy, lateral stepping, were associated with the longest latencies to get the foot off the ground while the body 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 EMG, reactive force and kinematic latencies except for earlier than normal muscle antagonist responses.³ and ⁵ The delayed latencies to lifting the stepping foot off the ground when using the lateral stepping strategy in PD subjects, are probably due to smaller than normal anticipatory postural adjustments under the step leg, which is weighted by the movement of the body CoM over it during the translation. Smaller than normal magnitudes and scaling of anticipatory lateral weight shifts, with late peaks, also characterize anticipatory postural adjustments in PD prior to voluntary step initiation.

However, unlike voluntary step initiation, lateral compensatory stepping was not significantly improved with levodopa antiparkinsonian medication.³ Levodopa replacement therapy did not change either strategy selection, stepping characteristics or number of falls, suggesting that levodopa does not improve compensatory stepping like 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 two behaviors that show so much resemblance.^{3,17} and ²⁶ The lack of improvement in lateral stepping responses for balance correction with antiparkinsonian medication is, however, consistent with previous studies showing lack of improvement of feet-in-place postural responses to backward surface translations.³ Our results suggest that compensatory stepping is organized by nondopaminergic pathways similar to automatic postural responses with feet in place, but unlike voluntary stepping.³ and ¹⁶ The lack of improvement in reactive balance control with levodopa replacement is also consistent with the lack of fall prevention in the ON state compared to the OFF state in PD.²⁷

One limitation of our study was that we were not able to analyze the parameters of the cross-over strategy due to the high number of falls and difficulty seeing markers. In the 3 PD subjects that we could measure the latency to step initiation when using a cross over strategy, the latencies were more than double their latencies for side stepping. Thus, the cross over strategy may have been due to passive leg motion as the platform translation unloaded this limb as the body fell laterally. In contrast, studies have shown that when elderly control subjects used a side stepping strategy, which requires active unloading before leg lifting, that their steps were slower.¹² In some trials, PD subjects appeared to first select a lateral step but it was very small, and ineffective and was then followed by a cross over step and fall. Thus, it is unclear whether the frequent falls associated with the cross over strategy in PD, but not control, subjects is due to their problems with strategy selection or to bradykinetic execution of the step.

The slow, late, small stepping associated with the most successful strategy of lateral stepping is consistent with bradykinetic postural responses reported previously.³ It is likely that the PD subjects were not able to quickly shift their weight adequately to quickly take a fast, large step. When PD subjects did not step at all this likely represented a failure to select 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.

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.²⁸ For example, since falls had a strong correlation with delayed step latency, probably associated with slow anticipatory postural leg unloading, larger lateral weight shift and faster step initiation should be targeted during therapy. Since lateral side stepping was the most successful strategy, therapists should be reinforcing this strategy (as well as compensatory grasping) in therapy. Studies have shown that paced stepping practice during self-initiated, medial-lateral stepping was modifiable.²⁹ Another study showed that repetitive training of compensatory stepping effectively increased step length, shortened step latency and increased step speed and carried over to voluntary gait parameters.³⁰ and ³¹

In conclusion, impaired lateral compensatory stepping strategies in PD can lead to falls and are not improved by dopamine replacement medication. Therapy programs aimed at improving lateral stability in PD should encourage a lateral stepping strategy with faster and larger steps.

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Figure 1.
Strategies in response to lateral platform translation.

Figure 2. 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) ($V=L/D$).

Figure 3.

Characteristics of sidestepping; comparisons of step latency, step length and step velocity.

a. Step latency. This histogram illustrates the time from lateral platform translation to initiation of a side step to maintain balance for control, PD OFF and PD ON groups. * $p > 0.05$, ** $p > 0.01$

b. Step length. This histogram compares the length of the side step among the control, PD OFF and PD ON groups. * $p > 0.05$, ** $p > 0.01$

c. Velocity of side step. This histogram compares the velocity of the side step among the control, PD OFF and PD ON groups. * $p > 0.05$, ** $p > 0.01$

Table 1

Characteristics of subjects with Parkinson's disease

Subject	Age	Gender	Years of PD	H&Y	UPDRS OFF	UPDRS ON	%Falls OFF	%Falls ON
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	37	0	0
7	66	M	5	3	44	5	0	0
8	56	F	14	3	44	32	0	0
9	53	M	13	4	42	5	56	15
10	39	F	15	3	40	13	57	57
11	67	F	3	5	32	6	100	100
12	58	M	28	3	21	30	100	0
13	76	F	3	2	21	11	0	0

Table 2

Group mean (SEM) percentage of trials using each strategy and percentage of trials with falls.

	Control	PD OFF	PD ON
Side Step			
% Trials	70 (12)	67 (13)	73 (12)
% Falls	1 (4)	17 (13)	14 (10)
Cross Over			
% Trials	30 (12)	29 (10)	15 (10)
% Falls	0	75 (15)	36 (22)
No Step			
% Trials	0	14 (10)	12 (8)
% Falls	0	100(0)	100(0)