



Published in final edited form as:

Arch Phys Med Rehabil. 2010 September ; 91(9): 1332–1338. doi:10.1016/j.apmr.2010.05.013.

Preparation for Compensatory Forward Stepping in Parkinson's Disease

Laurie A. King, PhD, PT, Rebecca J. St George, PhD, Patricia Carlson-Kuhta, PhD, John G. Nutt, MD, and Fay B. Horak, PhD, PT

From the Departments of Neurology (King, St George, Carlson-Kuhta, Nutt, Horak), Biomedical Engineering (Horak), and Physiology and Pharmacology (Horak), Oregon Health and Science University, Beaverton, OR

Abstract

Objective—To characterize preparation for compensatory stepping in people with Parkinson's disease (PD) compared with healthy control subjects, and to determine whether levodopa medication improves preparation or the execution phases of the step.

Design—Observational study.

Setting—Outpatient neuroscience laboratory.

Participants—Nineteen participants with idiopathic PD tested both in the on and off levodopa states and 17 healthy subjects.

Intervention—Moveable platform with posterior translations of 24cm at 56cm/s.

Main Outcome Measures—Compensatory steps forward, in response to a backward surface translation (24cm amplitude at 56cm/s), were categorized according to the presence of an anticipatory postural adjustment (APA) before stepping: no APA, single APA, or multiple APAs. The following step parameters were calculated: step latency, step length, center of mass (CoM) average velocity, and CoM displacement at the step initiation.

Results—Lateral APAs were evident in 57% and 42% of trials for people with PD in the off and on medication states, respectively, compared with only 10% of trials for control subjects. Compared with subjects with PD who did not have APAs, those subjects with PD who did make an APA prior to stepping had significantly later (mean \pm SEM, 356 \pm 16ms vs 305 \pm 8ms) and shorter (mean \pm SEM, 251 \pm 27mm vs 300 \pm 16mm) steps, their CoM was significantly farther forward (185 \pm 7mm vs 171 \pm 5mm) at foot-off, and they took significantly more steps to regain equilibrium. Levodopa did not affect the preparation or execution phase of compensatory stepping. Poor axial scores and reports of freezing in the United Parkinson's Disease Rating Scale were associated with use of 1 or more APAs before compensatory stepping.

Conclusions—Lateral postural preparation prior to compensatory stepping in subjects with PD was associated with inefficient balance recovery from external perturbations.

© 2010 by the American Congress of Rehabilitation Medicine

Reprint requests to Laurie King, PhD, 505 NW 185th Ave, Beaverton, OR 97006, kingla@ohsu.edu.

Presented to the International Society for Posture and Gait, June 21–25, 2009, Bologna, Italy.

No commercial party having a direct financial interest in the results of the research supporting this article has or will confer a benefit on the authors or on any organization with which the authors are associated.

Supplier

Keywords

Parkinson disease; Rehabilitation

Falls are an unfortunate and often disabling consequence of PD. A recent meta-analysis of 6 studies on falls in the PD population found that approximately 50% of people with PD will fall during a 3-month period.¹ Falls in people with PD are often related to inadequate postural responses.²⁻⁴ An individual's automatic reaction to loss of equilibrium can determine the outcome: a fall or a successful balance recovery. A successful recovery can consist of an upper extremity grasp, a feet-in-place postural adjustment, or a compensatory step to regain equilibrium.^{5,6} This article focuses on differences in preparation for forward compensatory stepping between subjects with PD and healthy control subjects.

The potential for postural instability increases dramatically as the base of support changes from a 2-leg to a 1-leg stance during a step.⁷ To prepare for this potential instability, an APA will move the body CoM laterally toward the stance leg by moving the CoP under the feet toward the stepping leg.⁶ APAs have been well studied for voluntary step initiation, but the role of APA for compensatory stepping in response to external perturbation is less clear.

When equilibrium is challenged by an unexpected external displacement of the body, an individual needs to react quickly with an appropriate postural strategy. If the perturbation has enough force to move the CoM beyond the capabilities of feet-in-place postural responses, then stepping is necessary to avoid a fall.⁸ The execution of a lateral APA before initiating a forward compensatory step, when the body CoM is already accelerating forward, may slow down the most critical action—a forward step to catch the falling body. McIlroy and Maki⁹ showed that healthy young and elderly control subjects seldom used an APA in response to fast, unpredictable surface translations. They hypothesized that the central nervous system downregulates anticipatory postural preparation when it is not necessary, or, in fact, may delay time to step initiation.

Previous studies showed that people with PD have bradykinetic APAs prior to voluntary step initiation compared with age-matched control subjects¹⁰ and that levodopa improves the amplitude of an APA before a voluntary step. Even in subjects with very early, untreated PD, APAs during voluntary step initiation are bradykinetic.¹¹ Much less is known about APAs associated with compensatory stepping in people with PD. Our previous study, using lateral perturbations, suggested that inconsistent use of APAs before lateral compensatory stepping may help explain the postural instability and abnormal compensatory stepping responses in people with PD.¹² In that study, levodopa did not improve the latency or the length of compensatory steps. It is uncertain whether the same pattern would be seen in forward stepping. Another study in our laboratory looked at forward compensatory stepping in people with PD who had freezing of gait and found that the most common postural preparations were multiple APAs (57% of trials) and of these, 69% of trials ended in a fall or inability to take a step.¹³ However, it is unknown how people with severe PD without freezing of gait and without falls prepare for forward compensatory stepping. The present study examines compensatory stepping strategies of people who had severe PD but not significant freezing of gait. We hypothesized that people with PD are unable to downregulate the preparatory phase of a compensatory step when it is not required or desired for a fast compensatory step like age-matched controls and that levodopa medication would not improve compensatory stepping.

METHODS

Subjects

Nineteen subjects with idiopathic PD and 17 aged-matched healthy control subjects recruited from the community participated. The demographic and clinical characteristics of the subjects are presented in table 1. There were no significant differences between the groups for age, weight, or height (see table 1).

The people with PD all had moderate to severe disease severity with levodopa-sensitive fluctuations as candidates for deep brain stimulation surgery, referred by a movement disorders specialist (J.G.N.). The subjects with PD and control subjects with other causes of balance impairment were excluded, such as peripheral neuropathy, musculoskeletal deficits, or history of stroke or head injury. Patients with PD who had debilitating postural tremor, dyskinesia, dystonia, or dementia that would interfere with testing were excluded. All subjects gave informed written consent for protocols approved by the institutional review board of Oregon Health and Science University.

Experimental protocol—All people with PD were tested at 8_{AM} in the off state, after at least 12 hours since their last dose of dopamine replacement therapy. They were retested in the on state 45 to 60 minutes after taking their medication. For the on and off state testing, subjects were rated on the UPDRS (Part III, Motor)¹⁴ and the Hoehn and Yahr scale.¹⁵ Then the subjects stood with each foot on dual forceplates of a moveable platform, with arms folded across their chest throughout each trial. They stood with their feet 4.5cm apart. Subjects wore a harness attached to the ceiling without any tension, and an assistant stood behind them for safety. Before platform translations, the subjects were instructed to look straight ahead at an art poster placed 3m (10ft) away and to have equal weight distribution between their feet, which was monitored on an oscilloscope. Subjects were instructed to keep their balance as best they could. Each subject experienced 3 trials consisting of a 24cm posterior platform translation at 56cm/s velocity. To recover equilibrium from this perturbation, all subjects required a compensatory forward step. The subjects also answered the UPDRS, Part II (Activities of Daily Living, Items 1–11) between sessions.

Data Collection and Analysis

The vertical forces under the initial stepping leg and the contralateral stance leg were assessed for the presence of an APA prior to stepping. For each subject, the weight traces were zeroed by subtraction of the mean baseline weight over 200ms before platform motion. We adhered to stricter criteria for APA than used in previous studies^{13,16} to avoid classifying asymmetric feet-in-place postural responses as lateral APA. Rather than an increase in the weight of the stepping foot compared with the stance foot, the stance foot also had to reduce weight from baseline level prior to the first step in order to be considered a lateral APA and had to occur at least 50ms after the onset of a perturbation (fig 1A, i and ii vs iii). Each trial was then categorized according to 1 of 3 strategies: no APA, 1 APA, or multiple APAs (see fig 1A for example). A group mean percent incidence of each strategy was determined for the control and PD groups, both off and on medication. The amplitude of the APA was normalized to the body weight of each subject. Not all subjects showed consistent step preparation strategy in every trial. Thus, strategy group (no APA, 1 APA, multiple APA) based on individual trials might feature the same subject in more than 1 strategy group.

A 3-dimensional representation of body motion was measured using a Motion Analysis system^a with 8 Falcon video cameras^a recording 23 reflective markers placed on body

^aMotion Analysis Corp, 3617 Westwind Blvd, Santa Rosa, CA 95403.

landmarks at 60Hz. CoM position was estimated from segment kinematics and body segment measurements.¹⁷ Step latency (foot-off time) was defined as the time from surface translation onset to the big toe beginning to lift off the floor or move forward relative to the platform. The anterior-posterior CoM displacement was noted at this time. Average CoM velocity was calculated for the duration of the foot movement phase of the first step. The AP step length was measured for the first step. Number of steps taken to recover equilibrium was also recorded.

The UPDRS Part III was used to measure disease severity in the people with PD. Axial measures were defined by the PIGD score, items 27 to 30¹⁸ of the UPDRS.

Statistical Analysis

Chi-square tests compared the effects of medication, trial order, and activities of daily living freezing score on preparation strategy. All stepping parameters were normally distributed (Shapiro-Wilk test) except for the number of steps after perturbation. To compare between PD and control groups, analysis of variance was used for normally distributed parameters. Because the assumption of group independence would be violated to compare preparatory strategy with associated clinical and stepping parameters, linear-mixed modeling, with subject as a random factor, and a variance components covariance structure were used. Differences in stepping characteristics (step latency, step length, CoM displacement at foot-off, CoM velocity during step) among 4 groups were analyzed: control, trials of subjects with PD without an APA, trials of subjects with PD with 1 APA, and trials of subjects with PD with multiple APAs. To analyze the effect of group and strategy on the number of steps taken after perturbation, nonparametric statistics were used.

RESULTS

Preparation Strategies

All subjects could independently recover equilibrium with compensatory stepping, except 2 people with PD who required light touch for stabilization after stepping. PD affected both the preparatory and the stepping phase. Figure 1 illustrates the postural preparation strategies used prior to compensatory stepping. During the brief acceleration of the platform, the vertical component of the gravito-inertial vector of the body was always momentarily reduced (0 – 50ms). The body was then perturbed forward, leading to an increased downward acceleration on the support surface. Trials without an APA (see examples in fig 1A, i and ii) often showed a small weighting asymmetry between the 2 feet with a mean medial-lateral CoP difference \pm SD of only 6.2 ± 5.2 mm. In contrast with trials without an APA, trials classified with a single APA (see fig 1A, iii) were associated with significantly larger peak medial-lateral CoP displacements (mean \pm SD, 29.2 ± 25.3) and were characterized by a decrease from baseline weight on the stance foot and an increase in weight on the stepping foot (not just an asymmetry). In some trials, there were a number of m-l weight shifts before the foot moved classified as multiple APAs (see fig 1A, iv).

Control subjects rarely had an APA before compensatory stepping, whereas patients with PD often exhibited 1 or more APA. Figure 1B shows the proportion of total trials in each subject group with no APA, 1 APA, and multiple APAs. Overall, the control subjects had no APA in 90% of all trials. In contrast, subjects with PD only stepped without an APA in 43% of trials in the off state and 58% in the on state. The proportion of trials with 1 or more APA tended to be reduced with levodopa, though not significantly (Pearson chi-square $\chi_{(df=1)}^2 = 2.4$; $P = .12$). People with PD used multiple APAs in 19% of trials in the off state and in 14% of trials in the on state, although control subjects never used multiple APAs. The preparation strategy was more variable in subjects with PD versus control subjects. Only 37% of the people with PD (7 of 19 in both the off and on medication states) maintained a consistent strategy (none, 1, or

multiple APAs) for all 3 trials compared with 71% (12 of 17) of control subjects. There was no significant effect of trial order on the distribution of strategy for control subjects ($\chi = 2.1$; $P = .36$), PD on ($\chi = 3.7$; $P = .44$), or PD off ($\chi = .45$; $P = .97$).

Preparation Strategy Relates to PD Clinical Scores

The postural instability and gait disability score from the Motor UPDRS (items 27, 28, 29, 30, arising from chair, posture, gait, postural stability, respectively) was significantly higher in people with PD using 1 or more APAs than people with PD using no APA (APA [$F_{1,100} = 9.66$; $P = .002$]) (fig 2A). Additionally, people with PD who reported freezing on the activities of daily living component of the UPDRS were more likely to use 1 or more APAs ($\chi = 11.03$; $P = .026$) (see fig 2B). The total Motor UPDRS score was not significantly related to the type of preparatory postural strategy used by subjects with PD.

Effects of PD on Postural Preparation

The latency of the APA was faster in PD compared with control subjects (214 vs 279ms; $F_{1,38} = 4.75$; $P = .036$). The peak amplitude of the APA prior to a step was not significantly different between PD and control subjects (means, 29.7 and 32.2mm, respectively; $F_{1,38} = 1.87$; $P = .18$). For the multiple APA strategy, the amplitude of the APA just prior to foot-off was larger than the initial APA (50.2 vs 19.6mm; $F_{1,28} = 11.1$; $P = .002$). In the PD group, levodopa did not affect the amplitude or latency of APAs ($F_{1,33} = .22$, $P = .64$; and $F_{1,33} = .19$, $P = .67$, respectively).

Effects of Levodopa on Compensatory Stepping

Levodopa did not affect any step characteristics (off vs on levodopa, mean \pm SE): latency to step (355 \pm 115ms vs 350 \pm 107ms), CoM displacement at foot-off (178 \pm 39mm vs 184 \pm 40mm), step length (271 \pm 136mm vs 281 \pm 140mm), and CoM velocity during first step (.45 \pm .15mm/s vs .47 \pm .16mm/s). Thus, the medication states were averaged for the following analysis of the effects of APA on step characteristics.

Effects of PD on Step Characteristics

Compared with control subjects, people with PD had longer step latencies, shorter step length, slower CoM velocity during stepping, larger displacement of the CoM at foot-off, and more compensatory steps. All of these step characteristics were worse when subjects used 1 or more APAs (see fig 3).

People with PD using an APAs before stepping had longer latencies to step initiation. The latency from perturbation to foot-off showed a significant strategy group effect ($F_{3,90} = 42.8$; $P < .001$) comparing control subjects and people with PD divided into groups according to those trials with 0, 1, and multiple APAs (see the grouping shown in fig 3). Contrast comparison tests revealed that the time to step was significantly longer between the people with PD with multiple APAs and all other people with PD and controls ($P < .01$ for each case). Trials of people with PD with no APA had similar step characteristics as control subjects with no APA. Step length was significantly longer for control subjects compared with PD with 1 APA ($P < .01$) or multiple APAs ($P < .01$). The forward length of the first step showed a significant main effect of strategy group ($F_{3,104} = 4.6$; $P = .005$), with shorter steps associated with more APAs.

There were significant differences in the CoM displacement and CoM velocity between subjects with PD and controls. The anterior displacement of the CoM at the moment of foot-off was associated with strategy group ($F_{3,86} = 18.3$; $P < .001$). Specifically, the CoM was farther forward at the time of foot-off for the multiple APA trials compared with all other strategies ($P < .01$ for each case). The average forward velocity of the CoM during the step

also differed between groups strategies ($F_{3,86} = 12.9$; $P < .001$). The CoM velocity was significantly slower in the multiple APA trials compared with all other trials ($P < .01$ for each case).

People with PD also took more steps to regain equilibrium, and the number of steps was associated with the preparatory postural strategy. On average (mean \pm SE), control subjects took 1.4 ± 0.5 steps, whereas people with PD took $2.3 \pm .95$ steps to regain equilibrium, a significant difference (Mann-Whitney $U < .001$). For people with PD, the use of an APA was associated with an increased number of steps (Kruskal-Wallis, $P = .003$) (see fig 3E), whereas it was not for the control group ($P = .323$). The number of compensatory steps was negatively correlated with the size of the first step (Spearman $R = -.45$; $P < .001$). However, the number of steps was not associated with the latency to initial foot-off ($R = .08$; $P = .27$). So although people with PD without an APA could sometimes step quickly, if the first step was small, then multiple steps were required.

When comparing the 10% of trials in which control subjects made APAs with control trials with no APA, similar relationships were found: a delayed foot-off, a CoM farther forward at foot-off, and a slower CoM velocity. However, the length of the forward step was approximately 150mm longer when a control subject made an APA compared with no APA, and the total number of steps was similar in both cases. These relationships contrast with those observed for subjects with PD making APAs and demonstrate good compensation by the control subjects.

DISCUSSION

Surprisingly, forward postural stepping responses to recover from a strong external perturbation may be impaired in people with PD because of excessive postural preparation rather than lack of postural preparation as has been proposed.¹⁹ Unlike voluntary step initiation, in which people with PD show smaller (or absent) APAs compared with age-matched controls,^{20,21} people with PD in our study showed similar size and more APAs prior to compensatory step initiation than our age-matched controls. Our results suggest that compensatory steps by patients with PD are preceded by postural preparation that delays the onset and shortens the length of the step, likely because the CoM is farther forward with slow velocity before the foot leaves the ground. Because postural preparation delays and shortens the step, compensatory steps are less stabilizing, and therefore multiple steps are often required, which could lead to festinating steps and falls.

Several studies have shown that healthy subjects do not generally use an APA prior to unpredictable compensatory stepping.^{9,17} McIlroy and Maki⁹ found that an APA was absent in 79% of the trials for healthy control subjects under a no instruction condition, similar to our protocol. They concluded that the APA, when present, was too small and brief to have a substantial influence on the lateral movement of the CoM, so it may represent a preplanned, stereotypical stepping response that was disrupted by the need to react rapidly to the unpredictable instability imposed by the perturbation.

It is unclear why people with PD persist in using an APA prior to compensatory stepping. It may be that people with PD and balance deficits cannot appropriately scale down this preplanned anticipatory phase as effectively as control subjects. In fact, we previously reported that people with PD had difficulty adequately scaling up the size of their APA for a voluntary step when the stance width increased.²¹ It is also possible that they use an APA in an attempt to become more stable prior to stepping, even at the cost of time. Another possibility is that the people with PD compensate for their weak in-place postural responses by slowing down their CoM with a lateral APA to give themselves enough time to take a step with weak push.

Thus, the slower CoM and the fast APA may be compensation for bradykinetic postural responses.²

We recently hypothesized that people with significant freezing of gait may have multiple APAs prior to a compensatory step because of difficulty coupling an APA with a step.¹³ This previous study found that people with PD who were recruited for freezing of gait used multiple APAs in over half of their compensatory stepping trials, despite normal latency and amplitude of their first APA. Unlike the current study, 86% of those healthy control subjects' trials included an APA prior to a compensatory step. The difference can most likely be explained by a smaller and slower surface translation and a different methodology for designating an m-l weight shift an APA (see Methods). Unlike our current study, the people with PD in our previous study also all had significant freezing of gait; many more subjects fell, or did not step, in response to the translations; and falling was associated with multiple APAs. Similar to the current study, levodopa did not change the postural preparation strategy or stepping characteristics.

Study Limitations

A limitation of the study is that subjects were always tested in the off medication state first, which could have allowed learning effects in the on state. However, we do not think this likely because of the lack of any effect of medication on postural preparation and the lack of any learning between the 3 trials within each medication condition.

Another study from our laboratory¹² characterized lateral stepping strategies in people with PD and found that although people with PD used the same strategy as controls (side step vs a crossover step after a lateral perturbation in approximately 70% of trials), the use of APAs differed between groups. The control subjects were consistent with 1 APA before sidestepping in all of their trials, whereas the people with PD only used an APA in approximately half of their trials. Consistent with the current study, when people with PD did use an APA, the latency and size of the APAs were similar to those of our control subjects, even though stepping latencies of those subjects with PD were slower than control subjects' latencies.

Why are APAs prior to voluntary step initiation reduced or absent in subjects with PD but are present at normal magnitudes prior to compensatory steps forced by external perturbations? One possibility is that the basal ganglia are more critical for activating APAs when steps are self-initiated.^{22,23} In contrast, when step initiation is triggered by an external cue such as a postural perturbation, the APA can be activated without involving the basal ganglia, although the coupling between the APA and the step is still impaired (eg, the long and variable latencies until step initiation).

CONCLUSIONS

Postural compensatory stepping is an important response to disequilibrium that requires careful assessment and focused intervention during rehabilitation. Clinicians should evaluate both the postural preparation phase and the execution phase of compensatory stepping. Long latencies to postural step initiation are not reflective of slow reaction times because the APAs are initiated quickly, but reflect poor coupling between the APA and the step. Inefficient postural preparation strategies results in slow step latencies, small step lengths, and an excessive number of steps for recovery of equilibrium, all which increase risk of falls.²⁴ Recent studies suggest that compensatory stepping may be improved with training.²⁵⁻²⁷ The traditional rehabilitation approach to improve step initiation is to practice postural weight-shifting, but our results suggest that patients with PD need to learn how to step quickly with larger steps in response to postural displacements, without initial weight-shifting, which delays and impairs effective steps. These findings should be considered in rehabilitation and balance training in people with PD.

Acknowledgments

We thank Triana Nagel, BS, for assistance in data collection. We also thank Edward King, MS, and Charley Russell, PhD, for assistance with equipment and programming.

Supported by the National Institutes of Health (grant nos. AG019706 and AG006457) and the Parkinson's Alliance.

List of Abbreviations

APA	anticipatory postural adjustment
CoM	center of mass
CoP	center of pressure
PD	Parkinson's disease
PIGD	Postural Instability and Gait Disorder Score
UPDRS	United Parkinson's Disease Rating Scale

References

- Pickering RM, Grimbergen YA, Rigney U, et al. A meta-analysis of six prospective studies of falling in Parkinson's disease. *Mov Disord* 2007;22:1892–1900. [PubMed: 17588236]
- Horak FB, Frank J, Nutt J. Effects of dopamine on postural control in parkinsonian subjects: scaling, set, and tone. *J Neurophysiol* 1996;75:2380–2396. [PubMed: 8793751]
- Horak FB, Dimitrova D, Nutt JG. Direction-specific postural instability in subjects with Parkinson's disease. *Exp Neurol* 2005;193:504–521. [PubMed: 15869953]
- Bloem BR, Valkenburg VV, Slabbekoorn M, Willemsen MD, van Vugt J, Beckley DJ. Postural instability and falls in Parkinson's disease. *Adv Neurol* 2001;87:209–223. [PubMed: 11347224]
- Horak, FB.; MacPherson, JM. Postural orientation and equilibrium. In: Smith, JL., editor. *Handbook of physiology*; section 12—exercise: regulation and integration of multiple systems. New York: Oxford Univ Pr; 1996. p. 255-292.
- Maki BE, McIlroy WE. Postural control in the older adult. *Clin Geriatr Med* 1996;12:635–658. [PubMed: 8890108]
- Winter, DA.; Ruder, GK.; MacKinnon, CD. Control of balance of upper body during gait. In: Winters, JM.; Woo, SL-Y., editors. *Multiple muscle systems: biomechanics and movements organization*. Springer-Verlag; 1990. p. 534-535.
- MacPherson, JM.; Horak, F. Neural control of posture. In: Kandel, E.; Schwartz, J.; Jessell, T., editors. *Principles of neural science*. 5th ed.. New York: Elsevier;
- McIlroy WE, Maki BE. Do anticipatory postural adjustments precede compensatory stepping reactions evoked by perturbation? *Neurosci Lett* 1993;164:199–202. [PubMed: 8152600]
- Burleigh-Jacobs A, Horak FB, Nutt JG, Obeso JA. Step initiation in Parkinson's disease: influence of levodopa and external sensory triggers. *Mov Disord* 1997;12:206–215. [PubMed: 9087979]
- Mancini M, Zampieri C, Carlson-Kuhta P, Chiari L, Horak FB. Anticipatory postural adjustments prior to step initiation are hypometric in untreated Parkinson's disease: an accelerometer-based approach. *Eur J Neurol* 2009;16:1028–1034. [PubMed: 19473350]
- King LA, Horak FB. Lateral stepping for postural correction in Parkinson's disease. *Arch Phys Med Rehabil* 2008;89:492–499. [PubMed: 18295628]
- Jacobs JV, Nutt JG, Carlson-Kuhta P, Stephens M, Horak FB. Knee trembling during freezing of gait represents multiple anticipatory postural adjustments. *Exp Neurol* 2009;215:334–341. [PubMed: 19061889]
- Fahn, S.; Elton, R. Unified Parkinson's disease rating scale. In: Fahn, S.; Marsden, D.; Calne, D., editors. *Recent developments in parkinson diseases*. London: Macmillan; 1987. p. 153-163.
- Hoehn MM, Yahr MD. Parkinsonism: onset, progression and mortality. *Neurology* 1967;17:427–442. [PubMed: 6067254]

16. McIlroy WE, Maki BE. The control of lateral stability during rapid stepping reactions evoked by antero-posterior perturbation: does anticipatory control play a role? *Gait Posture* 1999;9:190–198. [PubMed: 10575080]
17. Henry S, Fung J, Horak FB. Control of stance during lateral and anterior/posterior surface translations. *IEEE Trans Rehabil Eng* 1998;6:32–42. [PubMed: 9535521]
18. Bronte-Stewart HM, Minn AY, Rodrigues K, Buckley EL, Nashner LM. Postural instability in idiopathic Parkinson's disease: the role of medication and unilateral pallidotomy. *Brain* 2002;125:2100–2114. [PubMed: 12183355]
19. Purdue, MJ. The basal ganglia and posture. London: Pitman Medical Publishing Co, Ltd; 1967.
20. Burleigh A, Horak FB, Nutt JG, Obeso JA. Step initiation in Parkinson's disease: influence of levodopa and external sensory triggers. *Mov Disord* 1997;12:206–215. [PubMed: 9087979]
21. Rocchi L, Chiari L, Mancini M, Carlson-Kuhta P, Gross A, Horak FB. Step initiation in Parkinson's disease: influence of initial stance conditions. *Neurosci Lett* 2006;406:128–132. [PubMed: 16901637]
22. Hallett M. The intrinsic and extrinsic aspects of freezing of gait. *Mov Disord* 2008;23 Suppl 2:S439–S443. [PubMed: 18668625]
23. Frank JSHF, Nutt J. Centrally initiated postural adjustments in parkinsonian patients on and off levodopa. *J Neurophysiol* 2000;84:2240–2248.
24. Maki, BE.; Edmondstone, MA.; Perry, SD.; Heung, E.; Quant, S.; McIlroy, WE. Control of rapid limb movements for balance recovery: do age-related changes predict falling risk?. In: Duysens, JS-EB.; Kingma, H., editors. *Control of posture and gait*. Maastricht: International Society for Postural and Gait Research; 2001. p. 126-129.
25. Protas EJ, Mitchell K, Williams A, Qureshy H, Caroline K, Lai EC. Gait and step training to reduce falls in Parkinson's disease. *NeuroRehabilitation* 2005;20:183–190. [PubMed: 16340099]
26. Rogers MW, Johnson ME, Martinez KM, Mille ML, Hedman LD. Step training improves the speed of voluntary step initiation in aging. *J Gerontol A Biol Sci Med Sci* 2003;58A:46–51. [PubMed: 12560410]
27. Hall LM, Brauer S, Horak FB, Hodges PW. Adaptive changes in anticipatory postural adjustments with novel and familiar postural supports. *J Neurophysiol* 2009;103:968–976. [PubMed: 19955284]

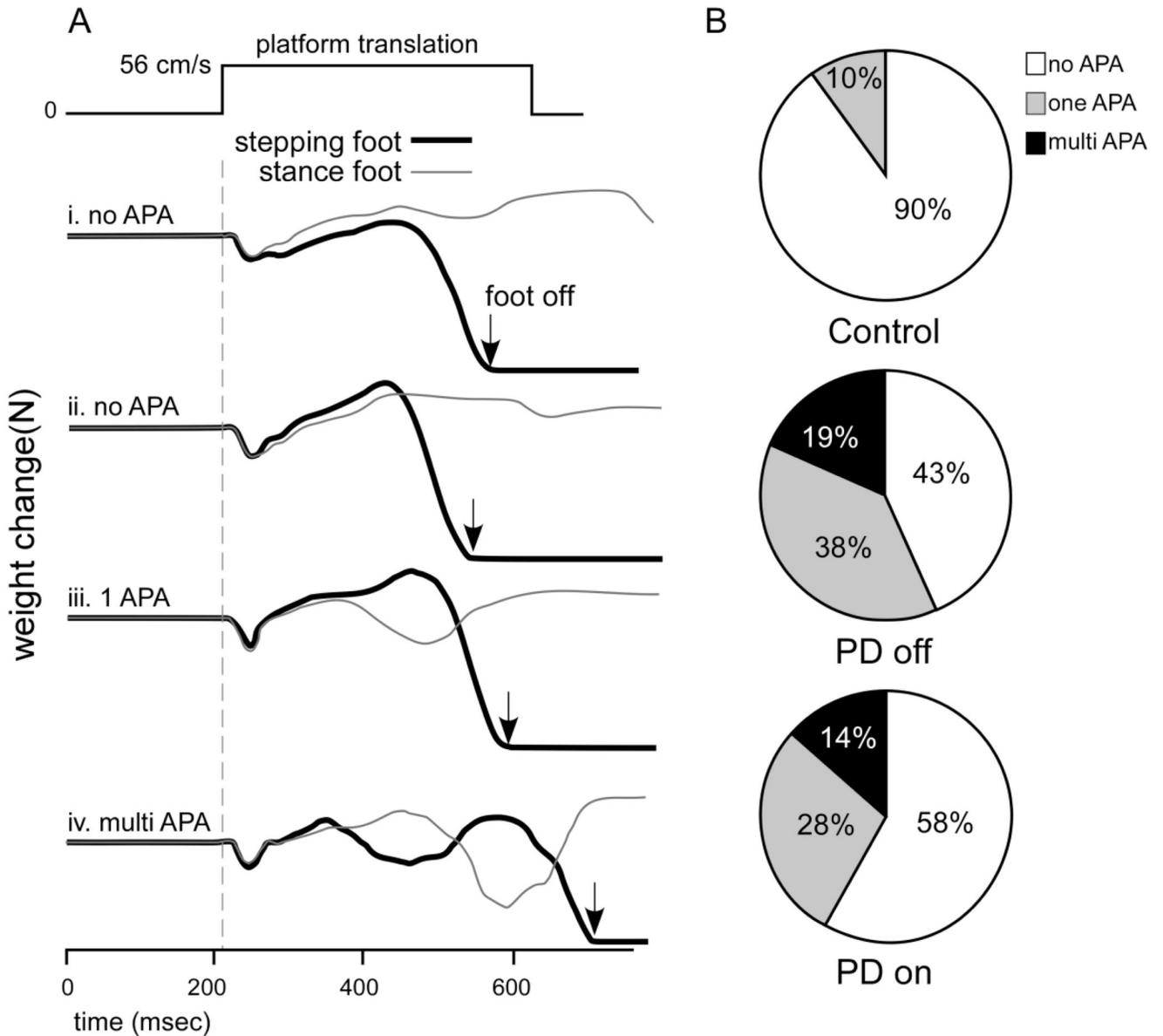


Fig 1.

Different postural preparation strategies were used in response to perturbation. (A) examples are shown with the weight under the stepping foot in black and the weight under the stance foot in gray. In (i), the weight increased more on the stance foot compared with the stepping foot, and in (ii), the weight of the stepping foot is weighted more than the stance foot, but because the weight on the opposite foot is also increasing, this is not considered an APA. A single APA from a subject with PD is shown in (iii), with a weight shift toward the stepping foot and away from the stance foot. A multiple APA from another PD subject is shown in (iv); the weight shifts diverge more than once before the step. The tracings shown in (i) and (ii) were common strategies for the control subjects, while (iii) and (iv) were common strategies for subjects with PD in both the off and on states. (B) The frequency of stepping strategies across groups. Out of the percentage of all trials, control subjects rarely exhibited an APA before stepping, whereas the people with PD in both the off and on states commonly used APA before lifting their foot off the floor. Abbreviation: multi APA, multiple APAs.

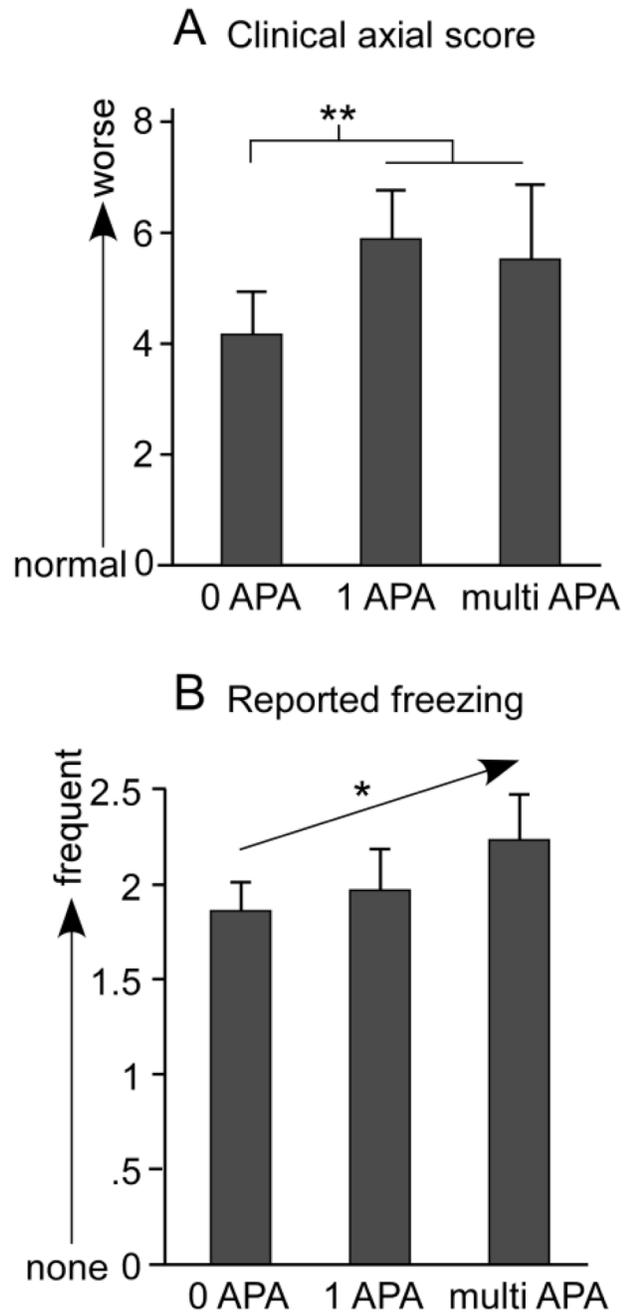
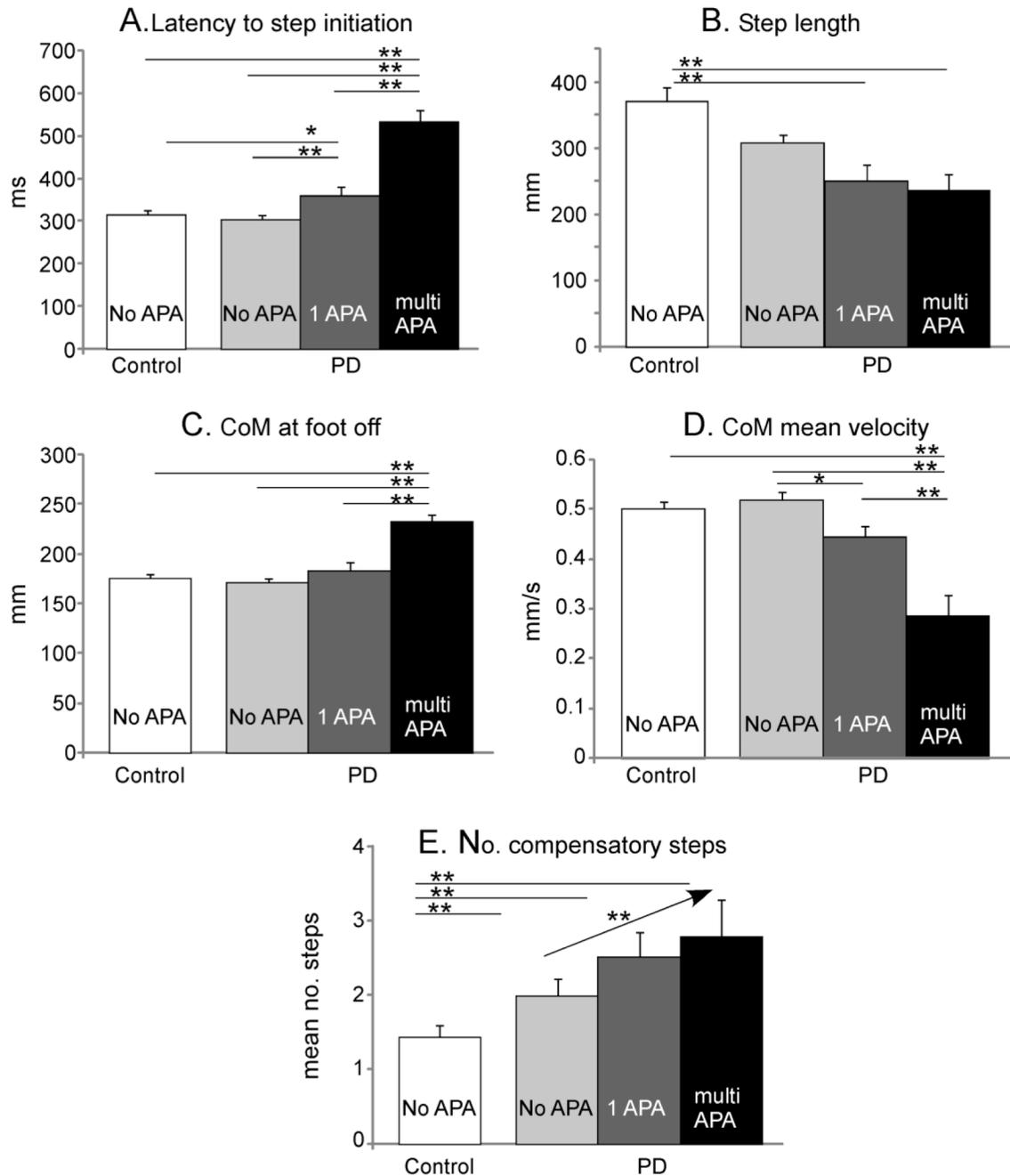


Fig 2. Postural preparatory strategy in people with PD related to (A) PIGD scores and (B) frequency of reported freezing; represented as group mean with SE. Abbreviation: multi APA, multiple APAs. * $P < .05$; † $P < .001$.

**Fig 3.**

Stepping characteristics of control subjects, who did not use an APA (90%), and trials of subjects with PD, divided into 3 strategies (no APA, 1 APA, multiple APAs). (A) The latency to step initiation from onset of the perturbation. (B) The forward length of the first step. (C) The forward position of the CoM relative to quiet standing at the moment when the foot was lifted. (D) the mean velocity of the CoM during the first step. Significant differences ($P < .05$) between groups are shown. (E) Number of compensatory steps. All data represented as a mean with SE. Abbreviation: multi APA, multiple APAs. * $P < .05$; † $P < .001$.

Table 1

Subject Demographic and Clinical Characteristics

Parameter	PD (n=19)	Control (n=17)
Sex	84% men	82% men
Age (yr)	65 ± 8 (52–76)	65 ± 8 (56–79)
Weight (kg)	86 ± 15 (62–108)	79 ± 16 (50–123)
Height (cm)	178 ± 8 (158–185)	175 ± 8 (163–188)
UPDRS III (off)	46.5 ± 14 (26–70)	NA
UPDRS III (on)	26.0 ± 12 (9–48)	NA
Hoehn & Yahr (off)	3.3 ± 0.9 (2.5–5)	NA
Hoehn & Yahr (on)	2.5 ± 0.8 (1.5–4)	NA
Diagnosis (y)	13.3 ± 4.8 (4–20)	NA

NOTE. Values presented as mean ± SD (range) unless otherwise indicated.

Abbreviation: NA, not applicable.