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Adaptation of gait termination on a slippery surface in Parkinson's disease

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Abstract

Parkinson's disease (PD) causes instability and difficulty adapting to changing environmental and task demands. We examined the effects of PD on the adaptation of gait termination (GT) on a slippery surface under unexpected and cued circumstances. An unexpected slip perturbation during GT was followed by a slip perturbation during GT under two conditions: planned over multiple steps and cued one step prior to GT. Feedforward and feedback-based responses to the perturbation were compared to determine 1) how PD affects the ability to integrate adaptive feedforward and feedback-based GT strategies on a slippery surface, 2) if adaptations can be implemented when GT is required within one step, and 3) if behaviour changes with repeated exposure.

Similar to the control group (n=10), the PD group (n=8) adapted and integrated feedforward and feedback-based components of GT under both stop conditions. Feedforward adaptations included a shorter, wider step, and appropriate stability margin modifications. Feedback-based adaptations included a longer, wider subsequent step. When cued to stop quickly, both groups maintained most of these adaptations: Foot angle at contact increased in the first cued stop but adapted with practice. The group with PD differed in their ability to adapt GT with slower, wider steps and less stability.

INTRODUCTION

Parkinson's disease (PD) is known to cause postural instability. Research has established that PD interferes with the integration of feedforward and feedback-based movements^{1, 2} and that a perturbation causing backward displacement, such as a slip, is destabilizing for someone with PD^{2, 3}. PD has also been shown to affect the ability to quickly change motor

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Conflict of interest statement

There are no known conflicts of interest for any of the authors.

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programs⁴⁻⁶. Neural impairments caused by PD may limit the ability to switch between walking and stopping or to develop the feedforward adjustments required to maintain stability while stopping gait on a slippery surface⁷. Neurodegeneration caused by PD may further limit the ability to adapt behaviour when stopping on a slippery surface: The striatum, along with the cerebellum and select frontal lobe regions, is involved in motor learning and adaptation⁸⁻¹⁰ as well as on-line modification of movements¹⁰ like those seen during anticipation of a perturbation.

Previous gait termination (GT) research in healthy participants reveals that adaptations to a known slippery surface include modifications in both feedforward and feedback-based movements. Feedforward adaptations include shorter steps onto the slippery surface¹¹⁻¹⁶, an increased stability margin^{11, 17}, a forward centre of mass (COM) shift^{11, 18-20} and a decreased foot-floor angle to reduce shear contact forces^{11-14, 16, 17, 20}. Adaptations to feedback-based responses include increases in the subsequent step length^{17, 19, 21, 22} and a more stable COM-base of support (BOS) relationship^{12, 19}.

While the ability of someone with PD to voluntarily adapt gait^{23, 24} and sit-to-stand movements²⁵ has been shown to be similar to controls, neither the greater challenge of GT nor the added difficulty of responding to an external perturbation like a slip has been examined. Past research has shown that participants with PD are able to integrate a feedback-based response while stopping on an unexpected, slippery surface⁷. This study, however, presents one of the first investigations into the *adaptation* of GT on a slippery surface in PD and addresses the following questions: 1) Can someone with PD integrate feedforward and feedback-based strategies to stop on a slippery surface? 2) Can this integration be implemented within one step? 3) If not, can someone with PD adapt movements with repeated attempts to stop within one step? Adaptive behaviours were examined by comparing an unexpected slippery stop to subsequent planned stops on the slippery surface. Following a series of planned stops, cued stops were elicited requiring GT within one step. The cued stops examined the ability to quickly generate adaptive behaviours. In the absence of adaptations, repeated exposure to the cued stops examined whether additional experiences enabled further adaptation.

We hypothesized that subjects with PD would have difficulty integrating the feedforward and feedback-based strategies required to adapt both planned and cued GT on a slippery surface and would require more experiences than healthy controls to show significant adaptations. Understanding the ability of someone with PD to adapt to changes in task demands would be useful in rehabilitation.

METHODS

Participants included eight participants with idiopathic PD (66.0 $\pm$ 8.3 years SD) and ten age- and gender-matched controls (65.4 $\pm$ 7.3 years SD) (Table 1). All PD participants had taken their usual medication within two hours of testing with no wearing off reported. The motor subscale of the Unified Parkinson's Disease Rating Scale was administered by a physiotherapist (range = 7 – 44). The severity of Parkinsonism was determined by a neurologist using the Hoehn and Yahr scale (range = 1–3). All participants walked independently and were free of orthopaedic, psychological, or other neurological disorders which could affect their ability to perform the tasks. All participants provided informed consent for protocols approved by institutional ethical review committees. The consent form stated that the surface may unexpectedly move when stepped on and participants were also given a verbal warning prior to signing the form.

All participants experienced three types of trials on a slippery surface in the following order: 1) one *unexpected slippery stop* which was cued one step prior to GT, 2) five *planned stops* on the slippery surface which were cued at the start of the trial, and 3) five *cued stops* on the slippery surface, introduced randomly across 15 walk-through trials, in which participants stopped on the slippery surface within one step.

Participants walked towards a set of lights at the end of the room which cued GT when illuminated. Without the cue, participants continued walking. The lights were controlled with an infrared light beam one step before the force plates in the middle of the room. To reduce anticipation, the unexpected slippery stop was elicited without knowledge of the perturbation after a series of cued stops on a non-slippery surface. In all cued stops, participants received the stop cue during the trailing limb step, stepped onto a force plate with their lead limb (first step), and completed GT (final step) by placing their trailing limb beside the lead limb. Starting location was manipulated so participants would naturally step on the force plate with their lead limb. To generate a slip perturbation, the force plate accelerated forward at contact for 0.15m at an average of 0.47m/s. This perturbation shares displacement and velocity characteristics with previous slip investigations^{22, 26}.

Kinetic data were captured from custom-made force plates using a QNX data collection system (480Hz sampling rate) and were used for identifying force plate movement. A high-resolution Motion Analysis System (Santa Rosa, CA) with seven cameras, (60Hz sampling rate), provided 3D coordinate information about body segment displacements. Markers were placed on anatomical landmarks including the xiphoid process and bilaterally on the ear, acromion process, olecranon, styloid process, anterior superior iliac crest, greater trochanter, lateral femoral condyle, lateral malleolus, heel, and fifth metatarsal head.

A 12-segment COM model was calculated using a custom-designed MATLAB program (Mathworks, Natick, MA) with data low-pass filtered at 6Hz. Walking velocity was calculated at contact onto the force plate. Decreased velocity represented a feedforward adaptation. Step length and width were calculated from the heel markers of both feet. Step length was defined as the anterior-posterior (AP) distance from the trail limb heel to the lead limb heel. Step width was defined as the absolute medial-lateral (ML) distance between heels. Step parameter changes during the first step of GT represented feedforward adaptations: Changes during the final step represented feedback-based adaptations. Foot dorsiflexion angle was calculated at contact on the force plate. A flatter foot decreases shear forces at contact and can be caused by a shortened step which brings the COM further forward. A flattened foot represented a feedforward adaptation despite a consistent frictional component in this paradigm.

A stability margin was calculated using an extrapolated COM position (xCOM) that includes both instantaneous COM height and velocity²⁷. The difference between the xCOM position and the edge of the BOS represented the stability margin. The xCOM position incorporates the velocity of the COM allowing comparisons between groups moving at different speeds: The BOS edge was represented by the fifth metatarsal marker on the foot that was stepping. A smaller AP stability margin during the first step of GT reflected an anterior shift in the COM revealing a feedforward adaptation^{12, 18}. A larger lateral stability margin also reflected a feedforward adaptation. An increase in both stability margins during the final step reflected increased stability during the feedback-based component.

To investigate the ability of someone with PD to integrate feedforward and feedback-based adaptations, a RMANOVA (2 groups $\times$ 6 trials) compared the unexpected slippery stop to the series of five, planned stops. To determine if adaptations could be generated within one step and maintained across the cued stops, the final planned stop was compared to the five

cued stops using a RMANOVA (2 groups $\times$ 6 trials). Significant trial effects were investigated with SNK post-hoc analysis. Interactions were further investigated using a one-way ANOVA for each group. Statistical significance was set at $\alpha = .05$. Between group effect sizes (Cohen's D) were calculated and are presented in table 2. Insufficient data caused two control participants (one from the unexpected slippery vs. planned stops, the other from the final planned vs. cued stops), and one PD group participant (walking velocity data only) to be removed from analysis.

RESULTS

Both groups implemented feedforward and feedback-based strategies to stop on a slippery surface. PD affected walking speed and step parameters in all conditions, and stability when cued to stop within one step.

Unexpected slippery stop vs. planned stops

Feedforward adaptations—Both groups stepped significantly shorter and wider onto the force plate in the first planned stop and again in the second planned stop (step length: $F=11.80$, $p<.0001$; step width: $F=6.62$, $p<.0001$) (Figure 1). Stability margins were also adapted during the planned stops (AP: $F=23.23$, $p<.0001$; ML: $F=6.67$, $p<.0001$): The AP stability margin decreased in the first planned stop and again in the second planned stop while the lateral stability margin increased in both the first and second planned stops. Walking velocity was not significantly different between trials ($F=1.25$, $p=.297$).

Walking velocity was slower in the PD group (.96m/s) compared to the control group (1.35m/s) ($F=16.96$, $p=.001$). The only group difference for the step and stability parameters was a shorter first step of GT in the PD group ($F=5.82$, $p=.0291$) (Figure 1) with no significant differences between groups for step width ($F=2.72$, $p=.1196$) or stability margin (AP: $F=.86$, $p=.3697$; ML: $F=3.08$, $p=.0996$).

Foot angle analysis revealed no group effect ($F=2.57$, $p=.1296$), a trial effect ($F=2.43$, $p=.0424$), and an interaction ($F=2.35$, $p=.0491$) (Figure 2). Post-hoc analysis did not reveal any significant differences between trials or within groups (PD: $F=.463$, $p=.801$; Control: $F=2.180$, $p=.072$). Qualitative assessment suggests that while the control group decreased foot angle with repeated exposure, the PD group did not show a clear pattern of change.

Feedback-based adaptations—For the final step of GT, both step length and width analysis revealed significant trial effects by increasing from the unexpected slippery stop to the first planned stop (step length: $F=14.22$, $p<.0001$; step width: $F=7.66$, $p<.0001$) but no group effects were evident (step length: $F=.91$, $p=.351$; step width: $F=1.0$, $p=.3326$). The AP stability margin analysis revealed no group ($F=1.72$, $p=.2093$) or trial effect ($F=.15$, $p=.9790$) but did show an interaction ($F=2.43$, $p=.043$); however, subsequent within group analysis did not reveal a trial effect in either group (PD: $F=1.0$, $p=.429$; Control: $F=.865$, $p=.512$). The lateral stability margin analysis was not significant for group ($F=.05$, $p=.8230$) or trial ($F=.98$, $p=.4338$).

Planned stops vs. Cued stops

Feedforward adaptations—Both groups increased walking velocity ($F=13.73$, $p=.0021$) (Figure 3) in the cued stops compared to the final planned stop. Foot angle at contact in the first cued stop was higher than the final cued stop ($F=3.15$, $p=.0128$) for both groups. The ML stability margin analysis revealed a trial effect ($F=2.41$, $p=.0450$) with no clear pattern in the data: the second cued stop was significantly less stable than the final planned and third

cued stop. There were no significant differences between trials for step length ($F=.18$, $p=.9707$), step width ($F=1.01$, $p=.4197$), or the AP stability margin ($F=1.69$, $p=.1493$).

Between group differences included walking velocity (Control=1.36m/s & PD=1.03m/s; $F=13.73$, $p=.0021$) and step width ($F=6.65$, $p=.0210$) with the PD group having slower, wider steps. Step length ($F=1.94$, $p=.1843$), foot angle ($F=1.39$, $p=.2575$), and stability margins (AP: $F=2.70$, $p=.1214$; ML: $F=2.70$, $p=.1213$) did not differ between groups.

Feedback-based adaptations—The final ML stability margin was the only variable to show a trial effect ($F=2.47$, $p=.0410$) with no clear pattern: the third cued stop was significantly more stable than the fourth cued stop. The final AP stability margin was significantly larger in the control group ($F=6.37$, $p=.0234$) and was the only variable to show a difference between groups. The remaining analyses showed no further significant trial or group differences: final step length (group: $F=2.44$, $p=.1394$; trial: $F=1.35$, $p=.2548$), final step width (group: $F=.00$, $p=.9640$; trial: $F=2.24$, $p=.0599$), final AP (trial: $F=1.54$, $p=.1883$) and final ML (group: $F=.57$, $p=.4631$) stability margin.

DISCUSSION

We hypothesized that integrating and adapting feedforward and feedback-based strategies to maintain stability while stopping on a slippery surface would be impaired by PD based on studies showing difficulty integrating feedforward and feedback-based movements^{1, 2}, quickly changing motor programs^{4–6}, maintaining stability^{2, 3}, adapting motor commands^{8–10}, and making on-line movement modifications¹⁰. We did not find differences in feedforward or feedback-based strategies between PD and control subjects when planning GT on a slippery surface nor was there a difference between groups in the number of experiences required for these adaptations. PD did, however, affect the ability develop appropriate strategies to stop within one step and maintain stability during cued GT.

PD did not affect the ability to adapt during planned stops

The adaptations observed in the first step of GT reflect a feedforward strategy to diminish the destabilizing slip. A shorter step and smaller AP stability margin indicate a forward COM shift thereby improving the COM-BOS relationship^{12, 19} to facilitate GT. This movement strategy is also seen in locomotion across a slippery surface^{12, 17, 19}. The increased step width and lateral stability margin reflect further stability enhancements generated before the slip perturbation.

A flatter foot is a proactive movement in anticipation of a slippery surface^{11, 13–17} that reduces shear contact forces. The control group used this strategy to reduce the effect of the slip perturbation. A flat foot can also be caused by a shorter step¹⁵ which was seen in the adaptation to the planned stops in both the control and PD groups.

Post-slip adaptations included a feedback-based modulation involving a longer and wider step. During an unexpected slip perturbation, a shortened step catches the backward falling COM by increasing the BOS^{11, 17, 26}. This step adaptation demonstrates improved balance control not requiring a larger BOS. The lack of post-slip change in the stability margins further suggests that both groups could control COM movement during the final step of planned GT on a slippery surface. It is also possible that feedforward modifications may have generated sufficient stability improvements so that post-slip adaptations to the stability margins were unnecessary.

PD affected the ability to generate adaptations within one step

Adaptations to the step parameters and the stability margins were maintained when planning time was reduced from multiple steps (planned) to one step (cued). Walking velocity, however, increased from the planned to the cued stops. The increased walking velocity suggests increased confidence in participants' ability to stop on the slippery surface and also indicates that participants did not anticipate the cue by slowing down. Foot angle changes required further adaptation following the first cued stop. This delayed adaptation has also been shown in young, healthy adults¹¹ and suggests that foot *placement* may be more effective in mitigating an anticipated slip than foot *angle* as evidenced in the step length and width adaptations occurring without any delay.

The PD group walked slower and increased step width throughout the cued stops perhaps to increase lateral stability. This strategy seemed to be successful as both groups were equally stable in the lateral plane. Even with advanced knowledge and proactive strategies, PD affected stability as seen by a smaller post-slip AP stability margin. With no difference in the BOS (i.e., step length) between groups, the decreased stability margin suggests that the PD group had difficulty controlling their COM.

People with PD can use external cues to initiate motor commands from extra-striatal sources such as the visuomotor cortex^{1, 6, 24, 29}. People with PD have also been shown to voluntarily adapt gait^{23, 24} and sit-to-stand movements²⁵ similar to healthy controls. The PD group may have used the visual light cue, and possibly the force plates which were distinguishable from the surrounding floor, to adapt to the slippery stops. Sensory feedback during the perturbation may also have cued adaptations. The similarity between groups suggests that most adaptations were produced through modifications via extra-striatal pathways.

This paradigm was chosen to create a controlled slip perturbation not possible with a slippery surface. True slips (e.g. on ice) are more destabilizing than platform slips²¹, partly by allowing the opportunity for a multi-directional slip. In addition, platform slips offer an end-point that may mechanically aid the slip-recovery, whereas real-world slips may not have a stable boundary; therefore, the generalizability of these results is limited.

These results indicate that participants with PD were able to use knowledge about and experiences with a slippery surface to integrate and adapt feedforward and feedback-based behaviours. The ability of the participants with PD to adapt to changes in task demands suggests that someone with PD could benefit from awareness and repeated use of external cues to facilitate balance control during rehabilitation^{9, 25, 29}. Further investigations should include more participants and could examine PD "OFF" medication to understand the control of stopping gait without levodopa.

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Research Highlights

- Parkinson's disease (PD) causes instability and difficulty with adaptation
- Participants with and without PD stopped on a slippery surface
- The group with PD group adapted movements similar to the control group
- The group with PD; however, had slower, wider steps and were less stable

Figure 1.

Average footfall locations for the first step of gait termination showing step length and width (+/- SE). PD group data are indicated by the darker markers. After the unexpected slippery stop, steps were significantly shorter and wider for the first planned stop (*) and then significantly shorter and wider again for the second planned stop (**) for both groups during the first step of GT. The PD group stepped significantly shorter than controls (^).

Figure 2.

Average foot angle at contact on the force plate ($\pm$ SE). Qualitative observation suggests that while the control group flattened the foot with repeated exposure, the PD group did not greatly adapt foot angle.

Figure 3.

Average walking velocity ($\pm$ SE). Walking velocity was significantly faster in the cued stops compared to the final planned stop (*). The PD group walked significantly slower than the control group (^).

Table 1

Participant characteristics for PD group.

ID	Age	Gender	PD duration	UPDRS	H & Y	Daily Medication
PD1	71	M	9 years	31.5	2.5	Carbidopa/levodopa (250mg x7), Sinemet (250mg (50/200) x1), Comtam (200mg x6), Propranolol (20mg x7)
PD2	68	M	6 years	36	2	Sinemet CR (250mg x3), Requip (2mg x3), Atenolol (25mg x1)
PD3	62	F	10 years	42.5	2	Sinemet CR (125mg (25/100) x2), Mirapex (0.5mg x3)
PD4	51	M	11 years	36.5	2	Sinemet (125mg (25/100) every 90 minutes), Requip (2mg x3), Amantadine (100mg x2)
PD5	78	M	8 years	44	3	Sinemet CR (x4), Requip (x 3) *
PD6	63	F	13 years	7	1	Sinemet (125mg (25/100) x2-4), Mirapex (50mg x4-6), Amantadine (100mg x2), Stalevo (50mg x5)
PD7	73	M	8 years	29	2	Sinemet CR (125mg (25/100) x3), Mirapex (0.5mg x3)
PD8	62	M	9 years	24	2	Sinemet CR (125 mg (25/100) x2), Mirapex (1mg x7 and 0.5mg x2), Comtan (200mg (1 tablet) x7, 100mg (0.5 tablet) x3)

* dosage information is not available

Table 2

Between group effect sizes

Variable	Comparison	F value	p value	Effect size
Unexpected slippery stop vs. Planned stops				
<i>Feedforward adaptations</i>				
Step length	PD < CT	5.82	.0291	2.04
Step width	ns*	2.72	.1196	1.36
AP stability margin	ns	.86	.3697	.71
ML stability margin	ns	3.08	.0996	1.61
Walking velocity	PD < CT	16.96	.001	8.98
Foot angle	ns**	2.57	.1296	1.58
<i>Feedback-based adaptations</i>				
Step length	ns	.91	.351	.53
Step width	ns	1.0	.3326	.57
AP stability margin	ns**	1.72	.2093	1.11
ML stability margin	ns	.05	.8230	.17
Planned vs. Cued stops				
<i>Feedforward adaptations</i>				
Step length	ns	1.94	.1843	4.33
Step width	PD>CT	6.65	.0210	3.97
AP stability margin	ns	0.97	.3398	.01
ML stability margin	ns	2.70	.1213	1.59
Walking velocity	PD < CT	13.73	.0021	5.78
Foot angle	ns	1.39	.2575	1.05
<i>Feedback-based adaptations</i>				
Step length	ns	2.44	.1394	1.21
Step width	ns	.000	.9640	.22
AP stability margin	PD<CT	6.37	.0234	2.68
ML stability margin	ns	.75	.3995	.59

ns* = no significant difference between groups;

ns*#-interaction found with no significant difference between groups

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