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

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Abstract

Parkinson's disease (PD) causes instability and difficulty adapting behaviour. To examine the effects of PD on adaptation to repeated, cued gait termination (GT) on a slippery surface, an unexpected slip perturbation during GT was followed by stops on a slippery surface under two conditions: planned over multiple steps and cued one step prior to GT. Measurements of feedforward and feedback-based responses were compared for group (PD versus control) and trial to determine 1) how PD affects the ability to integrate adaptive feedforward and feedback-based strategies to stopping on a slippery surface, 2) if adaptations can be maintained when the slippery stop is required within one step, and 3) if adaptations are not maintained, can behaviour be readapted with repeated exposure.

Similar to controls, the PD group was able to adapt and integrate feedforward and feedback-based components of GT to increase stability under both stop conditions. Feedforward adaptations included a shorter, wider step, and a smaller anterior-posterior and larger lateral stability margin. Feedback-based adaptations included a longer, wider subsequent step. When cued to stop within one step, both groups maintained most of these adaptations: Foot angle at contact increased in the first cued stop but re-adapted with practice. PD did not affect the ability to adapt to gait termination on a slippery surface over multiple steps or within one step.

Keywords

Parkinson's disease; gait termination; slips; adaptation

INTRODUCTION

Parkinson's disease (PD) is well known to cause postural instability. Past research has established that PD interferes with the integration of feedforward and feedback-based movements^{1, 2} and that a perturbation causing backward movement of the centre of mass (COM), such as a slip, is most destabilizing for someone with PD^{2, 3}. PD has also been

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

shown to affect the ability to quickly change motor programs⁴⁻⁶. The neural impairments caused by PD may limit the ability of someone with PD to switch between walking and stopping or to develop the internally-generated, feedforward movements required to maintain stability while stopping on a slippery surface⁷.

In addition to postural instability, neurodegeneration caused by PD may limit the ability of someone with PD to adapt motor behaviour to stopping on a slippery surface. The striatal region of the basal ganglia, along with the cerebellum and select frontal lobe regions, is involved in motor learning and adaptation⁸⁻¹⁰. The striatum is also involved in on-line modification of movements¹⁰ like those seen during anticipation of a perturbation.

Previous research on gait termination in healthy participants reveals behavioural adaptations to a known slippery surface involving modifications in the feedforward movements made before the perturbation as well as changes in the feedback-based movements made following the perturbation. Feedforward adaptations to slips include shorter steps onto the slippery surface¹¹⁻¹⁶, an increased stability margin^{11, 17}, a forward COM shift^{11, 18-20} and a decreased foot-floor angle to decrease shear forces at foot contact^{11-14, 16, 17, 20}. Adaptations to the feedback-based responses in locomotion over a slippery surface 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 gait termination nor the added difficulty of responding to an external perturbation like a slip has been examined in someone with PD. Past research has shown that someone with PD is able to integrate a feedback-based response while stopping on an unexpectedly slippery surface⁷. This study; however, presents one of the first investigations into the *adaptation* of gait termination on a slippery surface in Parkinson's disease and addresses the following questions: 1) Can someone with PD integrate feedforward and feedback-based strategies to stop safely on a slippery surface? 2) Can the same integration strategy be implemented in one step? 3) If not, can someone with PD readapt feedforward and feedback-based movements with practice? Adaptive behaviours were examined by comparing an unexpectedly slippery stop to subsequent planned stops on the slippery surface. Following a series of planned stops, cued stops on the slippery surface were elicited which required GT within one step. The cued stops revealed the ability of someone with PD to quickly generate adaptive behaviours. In the absence of persistent behaviour, repeated exposure to the cued stops examined whether additional experience enabled someone with PD to readapt their movements and stop safely within one step. We hypothesized that someone with PD would have difficulty integrating the feedforward and feedback-based control strategies required to adapt gait termination on a slippery surface and would require more experiences than healthy controls to show significant adaptations. In addition, we hypothesized that PD would negatively affect the ability to generate those adaptive movements within one step and that someone with PD would require a greater number of experiences with the cued stops to readapt their behaviour compared to healthy controls. Understanding the ability of someone with PD to adapt to changes in task demands with awareness of external cues and repeated practice with varied environments would be useful in rehabilitation.

METHODS

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) were included in the analysis (Table 1). All PD participants had taken their usual medication within two hours of testing and none reported a wearing off of their medication. The motor subscale (Part III) of the Unified Parkinson's

Disease Rating Scale (UPDRS) 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 were able to walk 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 protocols stated that the surface may unexpectedly move underneath their feet when stepped on and participants were also given a verbal warning prior to signing the consent form.

All participants experienced three types of GT trials on a slippery surface in the following order: 1) one *unexpectedly slippery stop* which was cued one step prior to gait termination, 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 placed randomly within 15 walk-through trials in which participants knew the cue required stopping on a slippery surface within one step.

Participants walked towards a set of lights located at eye level at the end of the room which, when illuminated, cued GT on a set of force plates in the middle of the travel path. Without the cue, participants continued walking to the end of the room. The lights were controlled with an infrared light beam one step before the force plates. To reduce anticipation, the unexpected slippery stop was elicited after a series of cued stops on a non-slippery surface without knowledge of the perturbation. In all cued stops, participants received the stop cue during the trailing (left) limb step, stepped on a force plate with their lead (right) limb (first step) and completed gait termination (second 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 foot contact for 0.15m at an average of 0.47m/s. This perturbation shares both displacement and velocity characteristics with previous slip investigations^{22, 26}; therefore, the perturbation trials were termed “slippery”.

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

A 12-segment centre of mass (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 slippery surface. A decreased velocity represents 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 represent feedforward adaptations: Changes during the second step represent modifications to the feedback-based response. Foot inclination angle was calculated at contact onto the force plate. A flatter foot serves to decrease shear forces at contact but also shortens the step and brings the COM further forward during that step. While the frictional component of the surface is consistent in this paradigm, a flattened foot represents a feedforward adaptation to improve stability during the perturbation.

A stability margin was calculated using an extrapolated COM position (xCOM) that includes both instantaneous COM height and velocity²⁷. The stability margin incorporates

both the COM position with respect to the BOS and the velocity of the COM allowing comparisons between groups moving at different speeds: With the same BOS, someone with a slower COM velocity would have a larger stability margin than someone with a faster COM velocity. The difference between the position of the xCOM and the edge of the BOS represents the stability margin. The BOS was represented by the marker on the fifth metatarsal on the foot that was stepping. A smaller AP stability margin during the step onto the moving surface reflects an anterior shift in the COM revealing a feedforward adaptation^{12, 18}. A larger lateral stability margin also reflects a feedforward adaptation. An increase in both horizontal stability margins during the second step of GT reflects increased stability during the feedback-based component of GT on a slippery surface.

To investigate the ability of someone with PD to integrate feedforward and feedback-based adaptations while stopping on a slippery surface, a RMANOVA (2 groups×6 trials) compared the unexpectedly slippery stop to the series of five, planned stops. Significant trial effects were then investigated with the SNK post-hoc analysis. Interaction effects were further investigated using a one-way ANOVA for each group separately to reveal within group differences. To determine if adaptations could be generated within one step, the final planned stop was compared to the first and final cued stop using a RMANOVA (2 groups×3 trials). Significant trial effects were further explored with the SNK post-hoc analysis. Statistical significance was set at $\alpha = .05$ for all comparisons. Insufficient data caused two control participants (one from the unexpectedly slippery vs. planned comparison, the other from the final planned vs. cued stops comparison), and one participant from the PD group (walking velocity data only) to be removed from analysis.

RESULTS

The group with PD was able to integrate adaptive feedforward and feedback-based components of GT on a slippery surface similar to controls. When cued to stop within one step, both groups maintained most of these adaptations.

Feedforward adaptations

Figure 1 illustrates that, for both groups, the step onto the force plate was significantly shorter and wider in the first planned stop and significantly shorter and wider again in the second planned stop (step length: $F=11.80$, $p<.0001$; step width: $F=6.62$, $p<.0001$) despite a significantly shorter step onto the force plate in the PD group compared to the control group ($F=5.82$, $p=.0291$). Analysis of step width showed no differences between groups ($F=2.72$, $p=.1196$). Similar to step width, forward and lateral stability, as measured by the stability margin, was similar between groups (AP: $F=.86$, $p=.3697$; ML: $F=3.08$, $p=.0996$) and adapted over the planned stop trials (AP: $F=23.23$, $p<.0001$; ML: $F=6.67$, $p<.0001$). The AP stability margin decreased in the first planned stop and was smaller again in the second planned stop. The lateral stability margin increased in the first planned stop and increased again in the second planned stop.

Walking velocity was slower in the PD group (.96m/s) compared to the control group (1.35m/s) ($F=16.96$, $p=.001$) with no significant differences between trials ($F=1.25$, $p=.297$). 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; however, nor did the separate one-way ANOVA within each group (PD: $F=.463$, $p=.801$; Control: $F=2.180$, $p=.072$). Qualitative assessment (Figure 2) suggests that while the control group decreased the foot-floor angle with repeated exposure, the PD group did not show a clear pattern of change.

Feedback-based adaptations

Both step length and width analysis revealed significant trial effects (step length: $F=14.22$, $p<.0001$; step width: $F=7.66$, $p<.0001$) but no group effects (step length: $F=.91$, $p=.351$; step width: $F=1.0$, $p=.3326$). Specifically, step length and width increased from the unexpectedly slippery stop to the first planned stop. 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 effect ($F=2.43$, $p=.043$). Subsequent within group analysis; however, 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 revealed neither an effect of group ($F=.05$, $p=.8230$) nor trial ($F=.98$, $p=.4338$).

Feedforward adaptations: Cued GT

The only difference between groups was walking velocity (Control= 1.35m/s & PD= $.99\text{m/s}$; $F=13.05$, $p=.0026$). There were no other differences between groups for step length ($F=1.88$, $p=.1907$), step width ($F=4.22$, $p=.0577$), foot angle ($F=1.28$, $p=.2762$), or stability margin (AP: $F=2.70$, $p=.1214$; ML: $F=2.43$, $p=.1399$). Both groups increased walking velocity ($F=13.82$, $p<.0001$) (Figure 3) in the cued stops compared to the final planned stop. Foot angle at contact in the first cued stop was higher than both the final planned stop and the final cued stop ($F=6.35$, $p=.005$).

Step length and step width onto the force plate showed no difference between trials (step length: $F=.20$, $p=.8206$; step width: $F=1.85$, $p=.1751$). Similarly, no significant differences between trials were found in the AP ($F=1.89$, $p=.1693$) or ML ($F=1.10$, $p=.3447$) stability margins.

Feedback-based adaptations: Cued GT

Final step length (group: $F=3.28$, $p=.0904$; trial: $F=1.60$, $p=.2188$) and width (group: $F=.03$, $p=.8665$; trial: $F=1.89$, $p=.1687$), as well as the final stability margins in the AP (group: $F=3.21$, $p=.0932$; trial: $F=.27$, $p=.7643$) and ML (group: $F=.57$, $p=.4631$; trial: $F=.80$, $p=.4594$) directions were not statistically significant between groups or trials.

DISCUSSION

We hypothesized that integrating and adapting a feedforward and feedback-based strategies to maintain stability while stopping on a slippery surface would be impaired by PD. PD has been shown to affect the integration of feedforward and feedback-based movements^{1, 2}, the ability to quickly change motor programs⁴⁻⁶ and maintain stability during a backward movement such as a slip^{2, 3}. In addition, the striatal region of the basal ganglia is involved in motor adaptations⁸⁻¹⁰ and on-line movement modifications¹⁰. We did not; however, find any differences between PD and control subjects in using feedforward or feedback strategies for GT on a slippery surface. Furthermore, PD did not appear to affect the ability to quickly develop appropriate strategies to stop safely.

People with Parkinson's disease adapt both feedforward and feedback strategies

The adaptations observed in the first step of GT reflect a proactive, feedforward strategy to diminish the destabilizing effects of the slip. A shorter step and smaller AP stability margin with repeated exposure reflect a forward shift in the COM position allowing the COM to be more easily and quickly moved within the newly-formed BOS^{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 increased lateral stability margin also reflect stability enhancements generated before the slip perturbation.

A flatter foot is often seen as a proactive movement in anticipation of a slippery surface^{11, 13–17} and helps reduce shear forces under that foot. 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 may have been a general characteristic of PD behaviour without being a direct response to the slip itself²⁸.

Post-slip adaptations show that the slip response is also modulated by a feedback-based strategy involving a longer and wider step. During an unexpected slip perturbation, a shortened step is used to catch the backward falling COM^{11, 17, 26}. This adaptation of a longer step shows a post-slip response to increase the size of the BOS and, hence, improve stability. The lack of post-slip change in the stability margins suggests that both groups were able to control COM movement during the final step of 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 not needed.

PD does not affect the ability to adapt quickly

Both the PD and control groups showed similar feedforward adaptations to stopping on a slippery surface required within one step. The 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 was one of the adaptations that did change from the planned to the cued stops. The increased walking velocity in both groups suggests that participants became more confident in their ability to safely stop on the slippery surface. The increased walking velocity also suggests that the cue to stop was not anticipated for by decreasing walking speed.

Foot angle at contact also showed a re-adaptation: Foot angle increased for the first cued stop only. The delay in the adaptation of the foot angle has also been shown in young, healthy adults adapting to stopping on a slippery surface¹¹. The delay suggests that foot placement is more effective in mitigating an anticipated slip perturbation than foot angle as evidenced in the step parameter adaptations being maintained without any re-adaptation required.

People with PD are able to use external cues to bypass the basal ganglia and initiate motor commands from sources such as the visuomotor cortex^{1, 6, 24, 29}. People with PD have also been shown to voluntarily adapt gait^{23, 24} as well as sit-to-stand movements²⁵ similar to healthy controls. In the present study, it is possible that the PD group used the visual light cue, and possibly the force plate, to adapt the first step of GT onto the slippery surface. Sensory feedback during the perturbation may also have been used as a cue for adaptations to the second step of GT. The similarity in behaviour between groups suggests that the adaptations were produced through modifications in extra-striatal pathways to generate and maintain the adaptations.

True slips (e.g. those on an ice surface) are more destabilizing than platform slips²¹. Platform slips offer an end-point of movement that may mechanically aid in the slip-recovery whereas real-world slips may not have a stable boundary. The platform also permits larger lateral loads, possibly making the platform movement safer than real ice.

These results indicate that people with PD can use knowledge about environmental conditions and experiences with a slippery surface to integrate and adapt feedforward and feedback-based postural and locomotor behaviour under externally cued conditions. The ability of someone with PD to adapt to changes in task demands suggests that patients with PD could benefit from awareness and repeated use of external cues and varied

environmental conditions to facilitate the maintenance of stability and movement during rehabilitation^{9, 25, 29}.

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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 unexpectedly 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 planned stops (*). The PD groups 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 ×7), Sinemet (250mg (50/200) ×1), Comtam (200mg ×6), Propranol (20mg ×7)
PD2	68	M	6 years	36	2	Sinemet CR (250mg ×3), Requip (2mg ×3), Atenolol (25mg ×1)
PD3	62	F	10 years	42.5	2	Sinemet CR (125mg (25/100) ×2), Mirapex (0.5mg ×3)
PD4	51	M	11 years	36.5	2	Sinemet (125mg (25/100) every 90 minutes), Requip (2mg ×3), Amantadine (100mg ×2)
PD5	78	M	8 years	44	3	Sinemet CR (×4), Requip (×3) *
PD6	63	F	13 years	7	1	Sinemet (125mg (25/100) ×2–4), Mirapex (50mg ×4–6), Amantadine (100mg ×2), Stalevo (50mg ×5)
PD7	73	M	8 years	29	2	Sinemet CR (125mg (25/100) ×3), Mirapex (0.5mg ×3)
PD8	62	M	9 years	24	2	Sinemet CR (125 mg (25/100) ×2), Mirapex (1mg ×7 and 0.5mg ×2), Comtan (200mg (1 tablet) ×7, 100mg (0.5 tablet) ×3)

* dosage information is not available