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Postural motor learning in Parkinson's disease: the effect of practice on continuous compensatory postural regulation

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Abstract

Introduction—Although balance training is considered the most effective treatment for balance impairments in Parkinson's disease (PD), few studies have examined if learning for balance control remains intact with PD. This study aimed to determine if learning for automatic postural responses is preserved in people with PD.

Methods—Eleven participants with moderate PD (68 ± 6.4 years; H&Y: 2–3) on their usual medication maintained balance on a platform that oscillated forward and backward with variable amplitude and constant frequency. Participants completed 42 trials during one training session, and retention and transfer tests following a 24-hour delay. Performance was measured by comparing spatial and temporal measures of whole-body centre of mass (COM) with platform displacements. Learning was compared between participants with PD and previously reported, age-matched older adults [15].

Results—Although postural responses in participants with PD were impaired compared to control participants, a majority of PD participants improved their postural responses with practice as revealed by reduced COM displacements and improved phase relationships between COM and platform motion. Rates of improvement were comparable between groups demonstrating preserved adaptive capacity for participants with PD. Similar to control participants, the PD group moved toward anticipatory COM control as a strategy for improving stability, exhibited short-term retention of performance improvements, and demonstrated generalizability of the learned

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CONFLICT OF INTEREST STATEMENT

FBH has an equity interest in APDM, a company that may have a commercial interest in the results of this study. This potential conflict of interest has been reviewed and managed by OHSU and the Portland VA Medical Center. The other authors have no conflicts of interest to report.

responses. Rate of improvement with practice, but not retention, was related to severity of motor impairments.

Conclusions—Patients with moderate PD on medication demonstrate retention of improvements in automatic postural responses with practice suggesting that intrinsic postural motor learning is preserved in this group.

Keywords

Parkinson's disease; posture; continuous perturbation; motor learning; automatic postural response

INTRODUCTION

Although balance training is considered the most effective rehabilitative treatment for balance impairments in Parkinson's disease (PD), few studies have examined whether the ability to learn a balance task is affected by PD [1–5] and only recently, has attention been given to whether or not PD impairs motor learning for automatic postural responses (APRs) [2, 6, 7]. APRs occur in response to externally-triggered disruptions to stability such as a slip or during continuous perturbations such as standing on a moving tram. The APR can involve feet-in-place responses when adjusting to small destabilizing forces, e.g. riding a tram, or single or multiple steps when reacting to a large perturbation, e.g. a slip. The goal of the present study was to examine if postural motor learning for a continuous, compensatory balance task, quantified by improved postural stability with training on an oscillating support surface, is preserved in patients with moderate PD.

Motor learning and motor control are often viewed as separate processes and although their independence is debatable (see [8] for review), the distinction between performance and learning suggests that the motor control impairments observed in PD do not necessarily predict loss of ability to learn a motor task. Motor learning is thought to be largely non-declarative, often occurring via trial and error without conscious awareness (e.g. learning to ride a bike) [9, 10]. Converging evidence suggests that non-declarative learning depends upon the basal ganglia and dopamine [8, 11–13]. Although few reports on postural motor learning in PD are available, existing studies have focused on *volitional* balance control, demonstrating mixed results related to longer-term retention of the acquired skill [1, 3–5]. Recently, our group has demonstrated learning for transient postural recovery (protective stepping) in individuals with PD [6, 7]. It is currently unknown how PD affects postural motor learning of a compensatory balance task requiring continuous postural regulation or how PD affects postural motor learning when the balance task lacks predictability.

Previously, we demonstrated preserved capacity for improvements in compensatory balance control in healthy older adults who underwent training on an oscillating platform with varying degrees of displacement, followed by retention testing 24-hours later [14, 15]. These improvements existed despite poorer postural stability in older, versus younger, participants. Furthermore, we demonstrated that performance improvements in both old and young adults possessed a degree of generalizability important for positive transfer of skill. In the current study, we hypothesize that participants with PD on their medication, when compared to healthy, aged-matched control participants, will exhibit impaired performance but preserved

postural motor learning as demonstrated by a) acquisition of adaptive APRs at a rate comparable to healthy, control participants and b) retention of performance improvements. We also hypothesize that participants with PD will demonstrate lack of transfer to a modified version of the task suggesting limits in the generalizability of the acquired skill.

METHODS

Participants

Eleven adults with idiopathic Parkinson's disease (4 males, 7 females) volunteered to participate. Participants ranged in age from 60–79 years (68 ± 6.4) and had mild to moderate PD as determined by a movement disorders neurologist (Hoehn and Yahr: 2–3). All participants took their anti-Parkinson medication within two hours prior to testing with no wearing off reported. The motor subscale of the Unified Parkinson's Disease Rating Scale (UPDRS) was administered prior to testing and ranged from 14.5–56 (Table 1). Participants were also assessed for freezing of gait (FOG) [16] and activities-specific balance confidence (ABC) [17] (Table 1). Participants were free of orthopaedic, psychological, or other neurological disorders that could affect their ability to perform the task. This study was approved by the University of Waterloo and Oregon Health and Science University research ethics boards. All participants provided informed consent prior to data collection. In addition, data from eleven healthy, age-matched, older adults (CTL), previously reported in Van Ooteghem et al [15 – “looped sequence” protocol], were compared with results of the participants in this study.

Procedures

The balance task required participants to stand on a hydraulically driven, servo-controlled platform that could translate horizontally forward and backward. Participants wore an unrestrictive, industrial safety harness tethered to a sliding hook on an overhead rail and were asked to maintain balance while looking straight ahead with arms crossed at the chest, avoiding stepping if possible. The platform oscillated at a fixed frequency of 0.5 Hz and variable amplitudes ranging from ± 0.5 cm to the largest amplitude that participants could withstand without stepping (maximum ± 15 cm).

Trials were 42-sec and composed of three segments of a 14-second, seemingly random sequence of platform oscillations. All trials for a participant were identical but the participant was not informed of the repetition. Each participant had a unique sequence of platform translations, which was generated randomly from a standard pool of amplitudes (range: 0.5–15cm). The training sequences were identical to those used for CTL participants [15]. For each participant, the maximum distance moved by the platform was scaled to a personal maximum as determined by a 20-second, constant amplitude practice trial (range: 11–15 cm; note 5/11 PD participants, but no CTL participants [15] required a reduction in perturbation amplitude). Testing consisted of six blocks of seven trials. To separate temporary effects of practice from more permanent changes in behaviour that would reflect learning, participants returned for a 3-block retention test approximately 24 hours following practice. Immediately following the retention test, participants completed one block of trials containing random sequences of sinusoidal platform translations (i.e. a transfer test) to

examine the generalizability of observed performance improvements. Each of the trials in the transfer block was unique; generated randomly from the standard pool. The same block of transfer trials was given to all participants.

Data Recording

A Motion Analysis System (Motion Analysis Corporation, Santa Rosa, CA) with six cameras captured three-dimensional spatial coordinate information about body segment displacements and platform movement. Reflective markers were placed bilaterally on the fifth metatarsophalangeal, lateral malleolus, lateral femoral condyle, greater trochanter, anterior superior iliac spine, iliac crest, styloid process, olecranon, acromion process, and lateral mandibular joint, and on the xyphoid process. A marker was also placed on the platform. Data were sampled at 60Hz and low pass filtered using a 2nd order, dual pass Butterworth filter with a cut-off frequency of 5Hz. The position of the centre of mass (COM) of each body segment in the antero-posterior (AP) direction was calculated using the kinematic data and anthropometric data provided by Winter [18]. Whole body COM position (in space) in the AP direction was derived from the weighted sum of the individual segment COM locations using a custom-designed MATLAB program (Mathworks, Natick, MA).

Data Analyses

To examine changes in posture control, the amplitude (gain) and timing (phase) of COM oscillations relative to platform oscillations were compared across trials (Fig. 1). Only the middle segment of each trial was analyzed. A reduction in COM gain and positive (leftward) shifts in COM phase relative to platform motion were considered to reflect improved compensatory balance control as participants stabilized their COM in space and reduced the degree of “lag” behind platform motion. Mean gain and mean relative phase of the COM were derived using the methods described in Van Ooteghem et al 2008 [19].

To evaluate practice-related improvements in performance (termed acquisition), COM gain and phase data from each trial were analyzed separately using mixed model ANOVAs to compare postural motor acquisition between PD and CTL participants across the six blocks of trials during training on day one. Although CTL participants received more training (Fig 2), only the first six blocks of trials were included in these analyses to match the amount of training received by participants with PD. Levene’s test for homogeneity of variance was conducted prior to the analysis of each variable.

To determine if learning occurred, paired t-tests (Bonferroni corrections) were used for planned comparisons between the first retention block on day two and the last training block on day one. A within-subjects design was used for the retention analyses to eliminate the potential influence of the longer training period for CTL participants. Generalizability of learning was explored by using paired t-tests to compare the first retention block to the transfer block.

An acceptable significance level for all tests was 0.05 and only those trials in which participants avoided stepping were included. In total, 17/693 trials (2.4%) were omitted from the PD group and 21/1001 trials (2.1%) were omitted from CTL group.

RESULTS

Acquisition of posture control

Significant improvements in postural stability, as measured by reduced COM gain and positive COM phase shifts, were observed with practice for a majority of participants with PD. Importantly, postural stability improvements occurred at a rate comparable to healthy CTL participants (Fig. 2). A main effect of block was observed for COM gain during the acquisition phase on day one ($F(3.17, 60.23)=10.32$; $p < 0.0001$; Greenhouse-Geisser); but there was no effect of group and no interaction between block and group (Fig. 2a). Although significant, the reductions in COM gain across the six blocks of practice were minimal for PD participants with a mean decrease of only 4.7% (0.70 ± 0.05 in early training to 0.66 ± 0.07 in late training); this was even more modest than the reductions observed in CTL participants (mean 5.7% after six blocks of training).

COM phase also showed a main effect of block ($F(2.37, 45.08)=39.56$; $p<0.0001$; Greenhouse-Geisser) and group ($F(1, 19)=12.33$; $p=0.002$), but no interaction (Fig. 2b). Although COM phase lag was significantly greater in early training (block one) for PD versus CTL participants ($-11.48^\circ \pm 3.88^\circ$ versus $-8.22^\circ \pm 2.47^\circ$), the magnitude of improvement was comparable, with an average shift of $6.36^\circ \pm 3.54^\circ$ for PD and $6.49^\circ \pm 3.39^\circ$ for CTL. Although a majority of CTL participants (7 out of 11) achieved phase lock (defined as less than 2° phase lag) following six blocks of practice or less, only two PD participants achieved in-phase performance with the same amount of training.

Retention and transfer of posture control in patients with PD

On day two, PD participants demonstrated maintenance of the improvements achieved during training, providing evidence for learning. Comparisons between the final block of practice on day one and the first retention block on day two showed no significant difference for COM gain (Fig. 2a) or COM phase (Fig. 2b). To examine the generalizability of the learned responses, a comparison was made between the first retention block and the transfer block to determine whether participants exhibited poorer performance on the transfer trials (i.e. lack of transfer). No significant difference existed between these blocks for COM phase (Fig. 2b). There was a significant difference for COM gain ($t(10) = 2.34$; $p=0.042$); however, it was in favor of smaller gain (better performance) during the transfer test (Fig. 2a).

Relationship between learning and performance impairments

A secondary analysis was conducted to examine the relationship between performance and clinical status using Pearson product moment correlation coefficients (r) to compare temporal control of COM (phase) and clinical outcomes (UPDRS motor score, disease duration, FOG score, ABC score) at baseline (mean COM phase for Day 1 Block 1), and during both acquisition (COM phase slope across all blocks on Day 1) and retention (mean COM phase Block 1 Day 2 minus mean COM phase for Block 6 Day 1). We chose to focus on COM phase control because it reflects how quickly postural adjustments are made; a key requirement for balance control [20, 21]. Since retention was intended to provide insight into the capacity for learning, only those participants who improved COM phase with training (slope > 0 , $n=10$) were included in the retention analysis.

PD participants who had greater motor impairments (higher UPDRS motor subscore) showed greater phase lag between COM and platform displacements in early training ($r(9) = -0.74$; $p=0.009$) (Fig. 3b), but also tended toward a greater rate of improvement during training ($r(9)=0.53$; $p=0.095$) (Fig. 3a and Fig. 3c). Degree of motor impairment was not significantly related to participants' ability to retain COM phase performance levels following the 24-h delay period ($r(8)=-0.20$; $p=0.59$). In addition, moderate relationships existed between 1) baseline COM phase and FOG scores ($r(9)=-0.58$; $p=0.064$), and 2) COM phase retention and mean ABC score ($r(8)=0.58$; $p=-0.078$); but these correlations were not significant. No other clinical outcomes were related to COM phase performance (Table 2 – supplementary material).

DISCUSSION

The present study provides novel insight into the capacity for improvement in compensatory balance control with training, even in PD participants who have significant pathology in the basal ganglia. Specifically, it focuses on the potential to train the APRs required to combat continuous, unpredictable perturbations during standing with feet in place. We show that despite poorer performance, a majority of PD participants demonstrated the ability to improve APRs as evidenced by rates of reduction in COM gain and COM phase lag that were comparable to the CTL group, and to maintain improvements across days of testing. These findings demonstrate a preserved capacity for short term, procedural motor learning for a task that requires continuous postural regulation. The results reported here are consistent with our previous study on compensatory stepping responses to discrete perturbations [6], demonstrating the potential for training-related improvements in APRs in individuals with PD.

Unlike compensatory stepping, perturbations in the present study were continuous; providing a rich environment for movement-produced feedback and conditions in which participants could maintain balance by relying on sensory-driven, rather than feed-forward control. The risk however, would be that response delays accompanying reactive control would leave participants vulnerable to loss of equilibrium during subsequent perturbations. Instead, PD participants moved from feedback toward feedforward control of COM motion as a strategy for improving performance (i.e. moved from a COM phase lag toward a COM phase lead relative to surface displacement). Predictive, feedforward control depends upon the ability of the CNS to gather information about perturbation characteristics and body orientation and serves to improve stability by influencing the timing and magnitude of the APR [22–24]. The challenge imposed on the CNS when continuous perturbation events lack predictability is that it is more difficult to exploit meaningful features from the perturbation environment and/or from the person-environment interaction in order to integrate such predictive control. In the present study, learning was observed for both spatial and temporal COM control, but improvements were far greater for COM phase perhaps because participants tuned in to the constant frequency feature of platform motion.

Given that postural motor learning is thought to be non-declarative and non-declarative learning depends upon the basal ganglia and dopamine, we propose three hypotheses to account for our findings. First, it is possible that compensatory postural motor learning is

mediated by a central network that relies more heavily on the cerebellum than the basal ganglia. The observed shift toward feedforward control of the COM suggests that learning involves development of a predictive strategy to control postural responses; supporting the potential involvement of cortico-cerebellar networks [25, 26]. Alternatively, it is possible that PD participants' ability to learn the balance task resulted from training in the ON levodopa state [7] and/or from re-weighting the contributions of other areas involved in a central postural motor learning network (e.g. medial frontal cortex, medullary locomotor areas, or medial cerebellum) to compensate for dysfunction in cortico-basal networks [27, 28]. Thirdly, it is possible the short-term protocol was not sufficient to reveal an altered time course for postural motor learning in PD versus CTL participants. Evidence suggests that learning deficits may be more relevant in later stages of learning (e.g. automatization) [8] and that for some tasks, people with PD may show early but not continued improvement with practice potentially related to disproportionate dysfunction of the dorsolateral versus ventral striatum in mild to moderately severe PD [6, 8].

Consistent with our previous findings, results of the present study demonstrate that participants in the PD group engaged in generalized learning since their postural stability was not disrupted during the transfer test. Evidence for generalized learning has important consequences for transfer of training-related improvements to similar balance tasks and offers some promise in light of evidence for reduced flexibility and increased context-specificity of motor adaptation and learning in PD [29, 30]. Transfer trials differed from learning trials with respect to amplitudes but not frequency of platform oscillations. It is possible therefore, that participants (PD and CTL) exploited the constant frequency feature of platform motion to improve performance. For PD participants, this may demonstrate a preserved capacity to extract relevant features from the perturbation environment. It is also possible that generalizability of the learned response is restricted to APRs with similar biomechanical demands. For compensatory stepping, our group reported no transfer when discrete platform translation for learning and transfer occurred in sagittal versus lateral planes [6]. Future work will aim to establish the degree of generalizability for postural motor learning.

A second important finding in the current study is that motor control impairments in patients with moderate PD appear to be independent of their ability to engage in postural motor learning. Disease severity, as defined by degree of motor impairment on the UPDRS, related more closely to postural performance deficits than to the capacity for postural motor learning. Practically, this suggests that although a patient with mild to moderate PD may perform a balance task with less COM control than a healthy participant, his/her rate of improvement and skill retention could be comparable. In fact, our results showed that participants with poorer performance in early training tended toward the greatest improvement in temporal COM control. Furthermore, markers such as disease duration, balance confidence, or freezing of gait tendency could not explain participants' potential for learning-related improvements in posture control.

Although we demonstrate the ability of PD participants with moderate disability to optimize postural responses with practice, further examination is needed to determine the longer-term benefits of balance training under conditions that rely on such non-declarative, trial-and-

error learning. Within this body of work, consideration should be given to developing longer-term training paradigms over weeks and months that can be tolerated by individuals with more severe disability to expand the clinical applicability of the current findings.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

- We examine learning for postural responses critical to fall avoidance.
- Learning is demonstrated using rates and retention of performance improvements.
- Impaired posture control does not preclude *learning* of automatic postural responses
- A shift from feedback toward anticipatory control drives performance improvements.

FIG. 1.

A representative trace of total body COM motion (in space) relative to oscillatory platform motion. COM is represented by the solid line. Platform motion is represented by the dashed line. Cycle-to-cycle phase values were computed in radians and converted to degrees. With equivalent peak amplitudes and the same timing, COM gain would be 1.0 and the COM relative phase difference would be zero degrees. In this example, COM gain is < 1.0 and relative phase is lagging (negative).

FIG. 2.

a) Group COM gain changes during acquisition (training), retention, and transfer. b) Group COM phase changes during acquisition (training), retention, and transfer. Striped markers represent additional CTL acquisition (training) blocks that were not included in the present analyses. Error bars represent SEM.

FIG. 3.

a) Individual participant data for COM phase performance improvements in the PD group. Representative changes in performance for participants with the highest and lowest UPDRS scores are highlighted with black and dark grey markers respectively. Despite greater motor impairment, the more severely affected participant (UPDRS = 56) showed a greater rate of improvement during training than the less affected participant (UPDRS = 14.5). Both participants demonstrated acquisition and retention. b) Relationship between degree of motor impairment (day 1 UPDRS motor score) and baseline COM control quantified by COM phase in early training (block 1)($p=0.009$). c) Relationship between degree of motor impairment (day 1 UPDRS motor score) and practice-related improvement in COM phase control (determine using COM phase slope across all blocks on day 1)($p=0.095$).

Table 1

PD participant demographics and clinical outcomes

Participant	Gender	Age (y)	Disease Duration (y)	Hoehn & Yahr Score	UPDRS ^a motor subscore (Day 1)	ABC ^b Score Total (mean)	Freezing of Gait Score
1	F	66	5	2.5	42	1150 (71.9)	10
2	F	65	6	2.5	56	1170 (73.1)	14
3	M	70	10	2	29	1375 (85.9)	4
4	F	72	5	3	30	1290 (80.6)	4
5	F	63	13	2	14.5	1290 (80.6)	5
6	M	62	4	2	41	1400 (87.5)	9
7	F	67	5	2	21	1537 (96.1)	6
8	F	74	5	2	31	1486 (92.9)	1
9	M	73	5	2.5	28	1225 (76.6)	13
10	M	69	11	2	48	1560 (97.5)	8
11	F	70	5	2	28.5	1255 (78.4)	9
Mean		68	6.7	2.2	33.4	1340 (83.7)	7.5
SD		4	3.1	0.34	12.2	142.8 (9.0)	4

^a Unified Parkinson's Disease Rating Scale;

^b Activities-Specific Balance Confidence