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Early biomechanical markers of postural instability in Parkinson's disease

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ABSTRACT

Current clinical assessments do not adequately detect the onset of postural instability in the early stages of Parkinson's disease (PD). The aim of this study was to identify biomechanical variables that are sensitive to the effects of early Parkinson's disease on the ability to recovery from a balance disturbance. Ten adults diagnosed with idiopathic PD and no clinically detectable postural instability, and ten healthy age-range matched controls (HC) completed the study. The first step in the response to a backwards waist pull was quantified in terms of strategy, temporal, kinematic, kinetic, and center of pressure (COP) variables. People with PD, compared to HC, tended to be less consistent in the choice of stepping limb, utilized more time for weight shift, used a modified ankle joint motion prior to liftoff, and the COP was further posterior at landing. The study results demonstrate that PD changes the response to a balance disturbance which can be quantified using biomechanical variables even before the presence of clinically detectable postural instability. Further studies are required to determine if these variables are sensitive and specific to postural instability.

1. Introduction

Postural instability is one of the most disabling symptoms of Parkinson's disease (PD) and one factor that increases the risk of falling, which occurs in up to 68% of people with PD [1,2]. Falls can have devastating effects on quality of life including fractures, hospitalization, loss of independence, and restriction of activities [3–6]. Interventions to reduce fall risk are likely most effective if they are implemented before someone falls, but current clinical assessments are not sensitive enough to detect postural instability prior to a fall [7–9]. Laboratory-based experiments are the necessary first steps toward developing more effective clinical measures of postural instability. Laboratory measurements of a balance recovery task may be more sensitive to postural instability earlier in the progression of Parkinson's disease, as has been recently demonstrated with postural sway [10,11].

Balance recovery variables, based on the biomechanical analysis of the step response to a balance disturbance, may effectively detect early signs of postural instability. The biomechanics of this step response have been widely studied to determine the effects of aging. Compared to young adults, older adults use a stepping strategy at smaller disturbances, take multiple, shorter steps, and step more laterally in response to an anterior or posterior perturbation [12–14]. They also generate larger peak ankle and hip torque and power [15–17], and show reduced hip flexion, knee flexion and extension, and ankle plantarflexion velocity [18]. Older adults with balance impairments, compared to those without balance impairments, use less ankle dorsiflexion and knee flexion prior to step liftoff, take more steps, and step more laterally in response to a backwards pull [12].

Previous studies of postural instability in people with PD have primarily focused on patients who already exhibit balance deficits and postural instability [19–23]. Jacobs and Horak demonstrated that people with moderate and severe PD, compared to healthy controls, utilized shorter steps [22], multiple anticipatory postural adjustments, and were less consistent in the choice of stepping limb in response to a backwards surface translation [24]. The authors suggested that this altered response may demonstrate an inability to quickly select an appropriate response, which has also been observed in young adults when they are unable to pre-select their stepping foot [25]. The step response to a balance perturbation prior to the presence of clinically recognized postural instability has not been studied.

The primary aim of this pilot study was to identify balance recovery variables that may be sensitive to the differences between people with PD but without clinically diagnosed postural instability, and healthy controls. Further studies are required to

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determine if these variables are sensitive and specific to postural instability.

2. Methods

2.1. Participants

Ten adults diagnosed with idiopathic PD (PD: age 63 (48–77) years, height: 167 (158–176) cm, mass: 76 (55–94) kg) and 10 healthy age-range matched controls (HC: age 67 (48–79) years, height: 165 (150–188) cm, mass: 69 (55–91) kg) completed the study (5 males and 5 females in each group). Exclusion criteria included dementia (MMSE < 24) [26], significant depression (BDI > 14) [27] and inability to ambulate without assistance. All participants gave written informed consent approved by the institution's Institutional Review Board (approval number 10330).

HC living independently were recruited from existing databases and the community. Medical history and a physical examination excluded those with cardiovascular, musculoskeletal and neurological impairments. People diagnosed with idiopathic PD were recruited from the institution's PD Center and were assessed with the Unified Parkinson's Disease Rating Scale (UPDRS). Exclusion criteria included postural instability (H&Y > 2), deep brain stimulators, or a history of significant musculoskeletal, neurological, or cognitive impairments other than those associated with PD. The participants with PD were instructed to maintain their regular medication schedule (Table 1) and were tested during the medication "on" phase, which was 2.08 ± 0.87 h after the administration of medications.

2.2. Task

The participant stood with arms crossed at the chest. For safety purposes, a harness connected to an overhead support was worn by the participant and a research assistant stood nearby to help prevent injury in case of a fall. The participant wore an adjustable but rigid waist harness that was connected to a weight-drop mechanism via a cable in the back of the harness. When triggered, the weight-drop mechanism produced a posterior waist pull by dropping a weight (20% body weight) with a pull distance equal to 8.7% of waist height [14]. The pull magnitude was large enough to ensure that each participant used a step response to recover balance. The participant was instructed to respond naturally to the posterior pull, which was repeated until three good trials were obtained. Examples of bad trials included not stepping onto a force plate or obstructing the cameras' view of kinematic markers. A maximum of six trials were performed by each participant.

2.3. Experimental measurements

Video, motion, and analog data (force plate, EMG, and load cell) were collected for each trial. Reflective markers, sampled at 120 Hz using a Vicon 512 (Vicon Peak, Lake Forest, CA) six camera system, were placed bilaterally on the 2nd metatarsal, lateral malleolus, heel, calf, and lateral femoral condyle. Bilateral tibialis anterior (TA) EMG activity was measured using a Noraxon telemetry surface electrode system (Noraxon, Scottsdale, AZ). Ground force reactions were measured using three AMTI force plates (Advanced Mechanical Technology Inc., Watertown, MA). The tensile force in the cable attached to the waist harness was measured using a biaxial custom-built load cell. Analog data were sampled at 1080 Hz using a 16-bit A/D data acquisition system controlled with the Vicon workstation.

2.4. Data analysis

Motion data were filtered with a Woltring filtering routine (MSE = 20) in the Vicon software. EMG data were full wave rectified and filtered using a second order low pass Butterworth filter (cutoff frequency = 50 Hz). Force plate and load cell data were similarly filtered (cutoff frequency = 20 Hz). Initial and final-time artifacts were minimized using forward and backward reflection of the data [28], and phase shift was eliminated by using forward and backward passes [29]. Data from all trials were processed using MATLAB (Mathworks, Natick, MA).

2.5. Strategy variables

The number of steps taken, a single vs. multiple step response, and consistency in the foot used for each initial step were determined. A multiple step response was defined as using more

Table 1
Characteristics of Parkinson's Disease Group.

Subject no.	Age (years)	Sex	UPDRS total	UPDRS motor	UPDRS #33	H&Y	Duration (years)	Medication	Dosage (mg/day)
1	77	M	37	27	1	2	1	Carbidopa/Levodopa	150/600
2	62	M	34	25	0	2	5	Carbidopa/Levodopa/Entacapone Trihexyphenidyl	150/600/800 4
3	65	F	10	9	0	2	4	Carbidopa/Levodopa/Entacapone Ropinirole	150/600/800 9
4	64	M	33	24	0	2	13	Carbidopa/Levodopa/Entacapone Carbidopa/Levodopa Pramiprexole	225/900/1200 100/400 0.75
5	73	F	22	17	1	2	3	Carbidopa/Levodopa	75/300
6	51	M	30	24	0	2	2	Carbidopa/Levodopa	150/600
7	48	F	11	9	0	2	2	Rasagiline	1
8	69	M	60	38	0	2	5	Carbidopa/Levodopa	100/400
9	63	F	18	14	0	2	12 ‘	Carbidopa/Levodopa Carbidopa/Levodopa CR Entacapone Pramiprexole	100/400 200/800 800 3
10	60	F	18	14	0	2	1	Carbidopa/Levodopa	75/300
AVG	63.2		27.3	20.1	0.2	2.0	4.8		
STD	8.9		15.0	9.1	0.4	0.0	4.3		

than one step to regain balance in any of the trials and consistency was defined as using the same foot for the first step in all trials. A step was defined as a change in the base of support that required foot liftoff and translation.

2.6. Temporal variables

Four events (disturbance onset, EMG onset, step foot liftoff and landing times) were used to define three temporal variables (reaction time: time between disturbance onset and first EMG onset; weight shift time (WST): time between reaction time and liftoff; and step duration: time between liftoff and landing times) with the liftoff and landing times reported relative to disturbance onset. The thresholds used to determine event times were: step foot liftoff (vertical force <3% body weight), step foot landing (vertical force >3% body weight), and EMG onset (rectified signal > mean plus five standard deviations of the EMG signal over a 50 ms window prior to disturbance onset). Previous studies have demonstrated that PD does not affect reaction time after an external perturbation [21,30,31]. Since our data confirmed this result ($p > 0.90$), reaction time was not considered further.

2.7. Kinematic and kinetic variables

Step length, step height, ankle angle, ankle torque, and vertical landing force were determined. Step length was defined as the distance between the heel marker locations at liftoff and landing. Step height was defined as the maximum vertical displacement of the heel marker between liftoff and landing. Step length and height were scaled to participant height.

Ankle angle and torque were determined using Vaughan's 3D inverse dynamics model [32]. Ankle plantarflexion (PF)/dorsiflexion (DF) angle was extracted at three time points (disturbance onset, liftoff, landing) and expressed relative to the initial configuration. Peak ankle angle and torque values were also extracted within two stages of the first step in the response: stage (1) disturbance onset to liftoff and stage (2) liftoff to landing. Within each stage, the maximum PF and DF angles and torques were determined relative to the values at the beginning of the stage. Ankle torque was scaled to the product of height and weight. The peak vertical landing force was the maximum vertical force after landing, scaled to body weight.

2.8. Center of pressure (COP) variables

The anterior–posterior (AP) and medial–lateral (ML) COP displacements were determined. The whole-body COP was analyzed from disturbance onset to landing of the first step. The AP and ML displacements of COP were determined at liftoff and landing of the first step relative to the COP location at disturbance onset.

2.9. Statistical analysis

Statistical analysis was performed in SPSS 15.0 (SPSS Inc., Chicago, IL). All three trials for each participant were used to evaluate group differences in strategy variables. A p-value ≤ 0.05 defined significance. A Fisher's two-tailed exact test was used to determine group differences in multiple vs. single step responses and consistency in choice of stepping limb. The Wilcoxon Rank Sum test was used to evaluate group differences in the number of steps in the response.

Multiple step response trials were averaged for each participant and analyzed by separate multivariate analysis of variance (MANOVA) models for temporal, kinematic, kinetic, and COP sets of variables to determine the group effect. MANOVAs were chosen to conservatively test for group differences. Follow-up t-tests were used to investigate the sensitivity of individual variables to the presence of PD, even if the MANOVA result did not indicate a significant group difference. Corrections for type I error were not performed because this was an exploratory study looking for variables that may be sensitive to postural instability.

3. Results

Ten people with PD and ten HC completed the study. All trials were included in the strategy analysis, but only multiple step strategy trials were included in the remaining analyses (temporal, kinematics, kinetics, COP), which left 8 participants in each group. An additional HC and participant with PD were not included in the ankle angle and torque calculations because of data collection problems with marker visibility. Anthropometric (weight and height), initial stance (stance width, initial COP location) and pull characteristics (peak, duration, impulse) revealed no group differences and were not considered further.

The backwards pull consistently resulted in a stepping response of between one and four steps without falling or external assistance required to regain balance. The MANOVA on the temporal variables (WST and step duration) showed a significant group difference ($F(2, 13) = 4.168$; $p = 0.04$). The MANOVAs on the kinematic ($F(8, 5) = 0.28$), kinetic ($F(5, 8) = 0.57$), and COP ($F(4, 11) = 0.23$) each showed no significant group differences, therefore only follow-up test results will be discussed further.

3.1. Strategy

The average number of steps (HC: 1.75 ± 0.57, PD: 1.77 ± 0.59) and the percentage of trials (HC: 90%, PD: 80%) that resulted in a multiple stepping strategy were similar between HC and PD. People with PD, compared to HC, tended to be less consistent in the choice of stepping limb but not to a significant level (HC: 80% vs. PD: 50%).

3.2. Temporal

The MANOVA on the temporal variables showed a significant group difference. The follow-up t-tests showed a significant group difference in WST but not in step duration (Table 2).

3.3. Kinematics and kinetics

First stage ankle angle variables showed significant group differences (Tables 2 and 3). The average ankle angle for each group

Table 2
Results for temporal, kinematic, and COP parameters.

	HC	PD
Temporal		
Weight shift time (ms)	222 (54)	500 (304)*
Step duration (ms)	113 (51)	153 (33)
Kinematics		
Liftoff angle (°)	1.5 (3.8)	−4.1 (3.6)*
Landing angle (°)	−1.3 (3.9)	−5.1 (5.2)
Step length (%)	8.2 (3.7)	10.2 (4.6)
Step height (%)	1.4 (2.0)	1.8 (2.5)
Center of pressure		
COP AP-liftoff (mm)	29.3 (25.3)	64.0 (48.9)
COP ML-liftoff (mm)	128.4 (19.2)	125.0 (33.9)
COP AP-landing (mm)	42.1 (16.8)	70.7 (36.6)*
COP ML-landing (mm)	129.0 (21.9)	127.2 (33.4)

$N = 8$ in each group for all parameters except liftoff and landing angle ($N = 7$ in each group). Liftoff and landing angles are relative to the initial configuration, (+) angle indicates plantarflexion.
* $p < 0.05$.

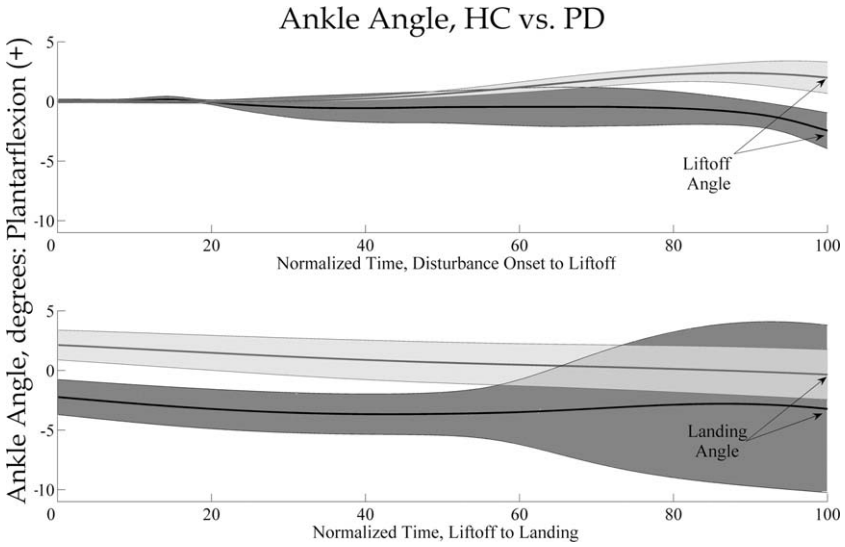

Fig. 1. Group Average Ankle Angle. Lighter trace is healthy controls (HC), darker trace is Parkinson's disease (PD). Top: disturbance onset to liftoff, bottom: liftoff to landing of first step. Solid lines are group averages, shaded areas are ±one group standard deviation. $N = 7$ for both groups.

Table 3
Kinematic and kinetic parameters in each stage. Stage 1 is disturbance onset to liftoff; stage 2 is liftoff to landing. Ankle angles are relative to configuration at the beginning of the stage. A (+) angle indicates plantarflexion.

Kinematics and kinetics by stage	Stage 1		Stage 2	
	HC	PD	HC	PD
Max ankle PF (°)	4.1 (1.7)	1.7 (1.7)*	0.4 (0.6)	2.4 (4.1)
Max ankle DF (°)	0.9 (1.3)	4.9 (2.7)**	3.9 (3.2)	3.6 (3.4)
Max PF torque (N-m/kg m)	0.2 (0.1)	0.2 (0.1)	0.03 (0.02)	0.03 (0.03)
Max DF torque (N-m/kg m)	0.04 (0.05)	0.01 (0.03)	0.02 (0.02)	0.0 (0.0)
Peak landing force (N/kg)	–	–	12.8 (1.9)	11.4 (1.6)

$N = 7$ in each group for all parameters except peak landing force ($N = 8$ in each group).
* $p < 0.05$.
** $p < 0.01$.

is shown in Fig. 1. During the first stage, the two groups showed a different ankle motion pattern: HC plantarflexed immediately after disturbance onset and then dorsiflexed slightly prior to liftoff, whereas people with PD dorsiflexed immediately with no plantarflexion. At liftoff, people with PD were in DF, whereas HC were in PF. At landing, both groups were in DF. People with PD, compared to HC, had larger peak DF angles and smaller peak PF angles during the onset of disturbance to liftoff stage. No group differences were found in the ankle motion in stage two, in the length or height of the first step, nor in any of the kinetic variables (Tables 2 and 3).

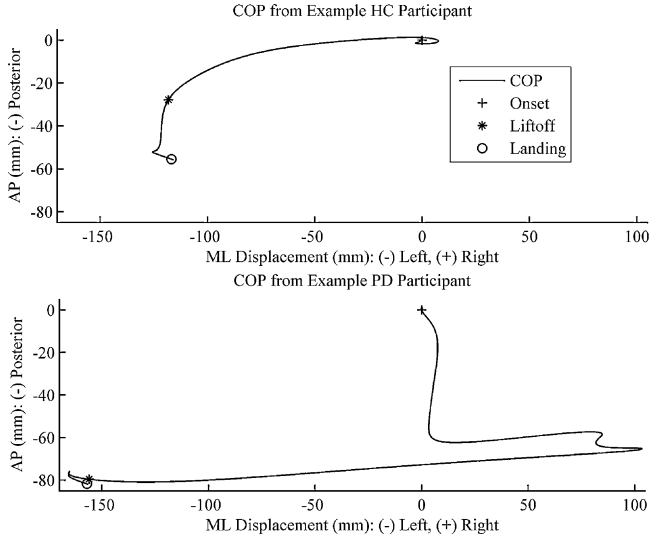

Fig. 2. Center of pressure (COP) plots from example HC (top) and PD (bottom) participant. Plots are centered about COP location at onset of disturbance.

3.4. COP

The COP was further posterior at landing in people with PD, compared to HC. No differences were found in the COP location at liftoff or in the ML location at landing (Table 2 and Fig. 2).

4. Discussion

Prior to any clinical indicators of postural instability, people with PD, compared to HC, demonstrated several significant differences in balance recovery variables used to quantify the response to a backwards waist pull. The observed differences were concentrated in the movement preparation phase for the first step taken in a multiple step response. The movement preparation phase (i.e. prior to liftoff of the first step) may be most affected by PD because of the important role that the basal ganglia play in the automatic selection and execution of motor plans [24,33].

PD did not affect the use of a single step response compared to a multiple step response. This result may have been influenced by the nature of the disturbance used in this study (i.e. backwards waist pull instead of a forward-lean-and-release or platform translation as used in other studies). People with PD tended to be less consistent in the choice of stepping limb, which has been previously reported [24].

PD caused a significantly longer WST, meaning that the center of mass moved further posterior before liftoff of the step, resulting in a more unstable response. The increased WST in people with PD is consistent with previous results by Jacobs, et al. who observed a longer liftoff time, the use of multiple APAs, and an inconsistent choice of stepping limb in response to surface translations [24]. The authors suggested that PD may cause an inability to quickly select an appropriate response because similar effects on balance recovery were seen in healthy participants when not allowed to pre-select their step foot [25].

PD did affect the kinematics (ankle motion and joint configuration) of the first step used in the response, but only prior to liftoff. The finding that HC were in PF at liftoff is consistent with results reported by Luchies et al. [14]. A PF orientation allows one to push off for the backwards step, whereas a DF orientation does not. Therefore, the DF orientation that was found in people with PD at liftoff may be a disadvantage in that no push off for a backwards step can be generated during balance recovery. PD did not affect the torque generated at the ankle in response to the backwards pull. The kinematic and kinetic results are consistent with a study which demonstrated that balance-impaired older women had altered ankle kinematics but similar joint torques and powers prior to liftoff, compared to older unimpaired women, in response to a backwards pull [12].

The differences in COP displacement indicated that people with PD moved further posterior prior to landing compared to HC. Taken together, it makes sense that a response with a longer WST and less push off would result in the participant falling further backwards before taking a step and therefore lead to a further posterior position at landing, which could impair balance recovery.

Study limitations include the small sample size and large number of variables tested. Additionally, the number of trials for each participant was not the same and data on the hip joint were not available to explain the results at the ankle joint and the displacement of the COP. Finally, people with PD had a wide range of ages (48–77), UPDRS scores (10–60), and disease duration (1–13 years), and the effects of these conditions on the response variables were not investigated due to the small sample size.

In conclusion, several differences were found, primarily in the movement preparation phase, in the response to a backwards pull in people with PD but without clinically diagnosed postural instability, compared to healthy controls. This study provides guidance for the development of further studies investigating early indicators of postural instability in PD. Future studies should investigate weight shift, ankle kinematics, and COP to determine their sensitivity and specificity to postural instability.

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Conflict of interest

None.

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