Gait Alterations on Irregular Terrain in Older Adults with and without Parkinson Disease: Fall Risk Implications

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Introduction: Persons with Parkinson disease (PD) are at risk for fall-related injuries as 60-80% of persons with PD fall annually. As a result of the motor and cognitive effects of the disease, the gait of persons with PD is distinguishably impaired as the disease severity progresses. Characteristic Parkinsonian gait includes a stooped torso and shuffling steps that are the result of overall reduced flexion and extension in the legs and nonzero velocity in the feet at the time of heel strike. Persons with PD have particularly high fall risks in comparison to healthy-older adults because their gait is impaired by both factors (age and the disease). The complexity of tasks involved and environments encountered while walking increase the gait impairments that PD inflicts, thus irregular terrain can add to the fall risk of this population. The purpose of this study was to characterize the gait of this fall-prone population on an irregular surface to accomplish the following goals: 1) Inform the general scientific community of the specific challenges that such environments present to those with PD so that such issues might be addressed 2) Provide biomechanical data to verify the ecological validity of a novel VR training environment being created for use in PD rehabilitation research.

Method: Nine patients with PD and nine healthy age-matched controls were recruited. Two 40cm x 60cm force plates (Bertec, Columbus, OH, USA) were imbedded into custom built, raised walkways (0.76 m x 7.3 m). Uneven terrain was simulated by modifying polyurethane faux rock panels and fixing them to the walkway surface. In total, 3 surface/slope conditions were simulated in addition to a control flat/level condition. Conditions included a cobblestone surface, an off-camber surface, and an off-camber cobblestone surface. The walkway at a 0 degree condition without the cobblestone served as the control. Video data were collected at (100 Hz) with Capture2D (C-Motion, Germantown, MD, USA) and 24 - V100:R2 cameras (NaturalPoint, Corvallis, OR, USA). Data were processed and calculations were performed using AMASS (C-Motion) and Visual3D (C-Motion).

Results: Surface rather than slope was shown to have a more significant effect on the gait parameters of focus (i.e. spatiotemporal measures, leg kinematics, and trunk stability measures). Specific gait changes exhibited by the participants with PD (on a 0 degree slope) included the following: 1) adoption of more conservative step patterns, 2) significant changes in the range of motion across all leg joints (while only the ankle was affected in the case of the control group), and 3) increased trunk COM acceleration variability in all directions (suggesting a challenge to stability in all planes of motion). In the case of surface effect on a 10 degree cross slope, the overall stability of the participants was more threatened than it had been due to the surface effect on the 0 degree slope.

Discussion: This study is unique in that it has identified gait patterns of participants with PD on conditions not yet tested with such a population (i.e. irregular terrain, cross slope, and a combination of the two). Overall, participants did not perceive the represented conditions to be particularly difficult, as indicated by their responses in the post-trial questionnaire; however, gait analysis results indicate that compensation strategies were employed differently by each group.

Practitioner Summary: Understanding how challenging terrain is traversed by high fall risk populations is important to developing prevention strategies and training environments. This study represents one of the first steps in quantifying gait on challenging terrain comprised of cobblestone and sloped surfaces in a population with PD. The results of this study will provide support to evaluate the ecological validity of a VR training environment being prepared by the research team. It may also help to identify the specific challenges that must be addressed to help train those with fall risks to better adapt their gait and reduce the risk of falling on irregular terrain.

Keywords: Parkinson Disease, Gait, Irregular Terrain, Falls

1. Background-Parkinson Disease

Parkinson Disease (PD) is second only to Alzheimer's in prevalence as a neurodegenerative disease affecting about 3% of the industrial world (De Lau & Breteler, 2006; Simuni & Pahwa, 2009). It is more prevalent among men after age 60 (Schrag, Ben-Shlomo, & Quinn, 2002). Since this disease mostly affects older adults and the global population is aging, prevalence of the disease is almost certainly going to increase in the future.

Diagnosis of PD is often performed through observing the presence of Akinesia or bradykinesia in combination with rigidity, tremor, and/or postural or gait instability (Edwards, Quinn, & Bhatia, 2008; Pahwa & Lyons, 2009).

Characteristic Parkinsonian gait includes a stooped torso and shuffling steps that are the result of overall reduced flexion and extension in the legs and nonzero velocity in the feet at the time of heel strike (Samii, Nutt, & Ransom, 2004). In addition, it has been noted that scuffs at midswing are known to occur, that heel strikes are often replaced with flat foot initial contact, and that steady state gait is achieved only after several strides (instead of just two or three as is often sufficient in healthy gait) (Levine, 2012). Furthermore, the task of turning is often characterized by a series of small shuffled steps instead of a pivot movement that is exhibited by those with healthy gait (Simuni & Pahwa, 2009).

1.1. Risk Factors

Approximately 70% of falls experienced by older adults take place during the task of walking (Berg, Alessio, Mills, & Tong, 1997; Norton *et al.*, 1997), often resulting from an initial ‘slip, trip, or loss of balance (Lord, Ward, Williams, & Anstey, 1993; Menant *et al.*, 2009). Perturbations/irregular terrain and poor visibility are common causes of falls, as are a number of other factors including footwear (which has also been linked to 45% of falls among older populations) (Berg *et al.*, 1997; Gabell, Simons, & Nayak, 1985). Furthermore, age related factors exist which specifically put older populations at risk for falls. Such factors include lateral instability which is particularly threatening because it specifically increases one's risk of lateral falls which are more likely to result in hip fractures than falls in other directions (Maki & Mcilroy, 1996; Woledge, Birtles, & Newham, 2005). Hip fractures in turn result in greater likelihood of mortality (Greenspan *et al.*, 1994; Norton *et al.*, 1997).

Age factors beyond general instability associated with falling include reduced vision, peripheral sensation, leg strength and reaction time (Lord & Ward, 1994; Menz, Lord, & Fitzpatrick, 2003). As many as 30% of community-dwelling older adults fall each year compared to 60-80% of persons with PD (Tinetti, Speechley, & Ginter, 1988; Wood, Bilclough, Bowron, & Walker, 2002). Persons with PD have particularly high fall risks in comparison to healthy-older adults (Axer *et al.*, 2010; Hausdorff, Rios, & Edelberg, 2001).

Persons with PD have an increased risk of falling in comparison to both healthy age-matched adults as well as those adults with other neurological disorders. Those with PD who also exhibit a fear of falling (i.e. 'lack of confidence to be able to perform activities without falling' have an even greater risk of recurrent falls compared with those without such a lack of confidence (Lindholm, Hagell, Hansson, & Nilsson, 2014).

Past studies involving irregular and uneven terrain have revealed a correlation between age and balance maintenance under such conditions (Marigold & Patla, 2008; Menant *et al.*, 2008).

Uneven terrain has been shown to affect the gait of healthy elderly individuals in particular in some of the following ways: increases step variability, decreases trunk variability, and decreases head variability (Berg *et al.*, 1997; Marigold & Patla, 2008; Menz *et al.*, 2003; Norton *et al.*, 1997; Thies, Richardson, & Ashton-Miller, 2005).

No studies exist which have reviewed the effects of cross-slopes on the biomechanics of older or impaired populations. As lateral falls are prevalent and severe among these groups, it is beneficial to review effects of variable terrain on gait adaptations in this high risk population.

1.2. Virtual Reality Training

Gait training involving higher intensity exercises as well as multi-sensorial feedback is effective with PD (Herman, Giladi, Gruendlinger, & Hausdorff, 2007; Nieuwboer, Kwakkel, & Rochester, 2010). A growing trend integrates VR into exercise regimes in order to augment their efficacy. Overall studies have shown that

VR rehab environments are more effective than less ecologically valid approaches and the training effects are transferrable to physical environments (Mirelman *et al.*, 2011; Riess, 1998).

The purpose of this study was to compare and characterize gait parameters (i.e. kinematic and spatial temporal) on different terrains for individuals with PD. The overall goal of this study was to provide additional information to the body of knowledge that informs fall prevention and intervention programs using virtual training environments.

2. Methods

Eleven participants with mild to moderate PD (all males, 69.91±11.63 years old) were recruited to provide feedback about falls and the factors associated with falling. These data informed the selection and construction of the testing environment in the laboratory for the gait study (Figure 1). A 'fall' was defined as a sudden, uncontrolled, unintentional, downward displacement of the body to the ground or other object, excluding falls resulting from violent blows or other purposeful actions; and a 'near fall' was defined as a sudden loss of balance that does not result in a fall or other injury, which could include an instance in which a person slips, stumbles or trips but is able to regain control prior to falling. All documents and procedures were approved in advance by the University of Utah Institutional Review Board.

Two 40cm x 60cm force plates (Bertec, Columbus, OH, USA) were imbedded to be flush with the surface of a raised 0.76 m x 7.3 m walkway. The walkway is supported by a series of five adjustable jacks on both sides and provides fore/aft and cross-slope capability. Uneven terrain was simulated using faux rock panels. The sections of the panels over the force plates were isolated to prevent the transfer of force to the force plates during gait events occurring outside of the boundaries defined by the force plate edges (Figure 1b). In total, 3 surface/slope conditions identified as being difficult from the questionnaire were simulated and compared to a control flat/level condition (Figure 1 c-f). These conditions included a cobblestone surface, an off-camber surface, and an off-camber cobblestone surface. The 0 degree condition without the irregular terrain served as the control.

Figure 1 Embedded Force Plates and Irregular Terrain Environments

In order to minimize risk of injury during the trials, a fall protection harness and overhead safety rail was integrated into the experimental setup. The following biomechanical parameters were evaluated in this study.

2.1. Spatiotemporal Parameters

- Speed (m/s)
- Cadence (steps/min)

- Step Length (m)
- Step Width (m)
- Step Width Variability (i.e. standard deviation of separate step width measurements averaged for the purpose of the step width)
- Double Limb Support (i.e. as defined with respects to total gait cycle time)
- Single Limb Support (i.e. as defined with respects to total gait cycle time)

Step parameters were normalized to leg length as done in previous studies. (Voloshina, Kuo, Daley, & Ferris, 2013)

2.2. Kinematics Parameters

The kinematic parameters were measured through model based calculation functions and inverse dynamics in Visual3D (C-Motion, Germantown, MD, USA):

- Ankle range of motion (i.e. defined separately in the transverse, sagittal, and coronal planes as the difference between the average min and average max angle values)
- Knee range of motion (i.e. defined in the sagittal plane as the difference between the average min and average max angle values)
- Hip range of motion (i.e. defined separately in the transverse, sagittal, and coronal planes as the difference between the average min and average max angle values)
- Functional leg length (i.e. defined as the average linear distance between the hip joint center and ankle joint center per trial)

2.3. Stability Parameters

The trunk/stability parameters of focus, as measured through model based calculation functions and inverse dynamics in Visual3D (C-Motion, Germantown, MD, USA) were as follow:

- Trunk range of motion (i.e. defined separately in the transverse, sagittal, and coronal planes as the difference between the average min and average max angle values)
- Trunk COM Acceleration RMS (i.e. the more direct measures of stability selected for this study as measured anterior/posterior, medial/lateral, and vertically)

Study parameters were grouped into spatiotemporal measures, leg kinematic measures (which included functional leg length because it is a direct related to the kinematics of the knee), and trunk motion and stability measures. Each group was then used as the basis for three separate mixed design repeated measures MANOVA tests. In each test, health (i.e. healthy vs. PD) was the between subjects factor; surface (i.e. hard vs. uneven/faux panel), cross-slope (i.e. 0 degrees vs. 10 degrees), and, in the case of the kinematic group MANOVA, leg position (i.e. down-slope leg vs. upslope leg or right vs. left leg in the case of the 0 degree conditions) were the within subject factors; and each metric was a dependent variable

3. Results

The study population was comprised by two groups (Table 1). Nine healthy older adults (HA) and nine adults with PD were recruited.

Table 1. Population Demographics for each group: mean (stdev)

Group	*N Female*	*N Males*	*age*	*weight (kg)*	*height (m)*	*UPDRS score*	*H&Y score*
HA	4	5	67.6 (8.0)	74.5 (5.6)	1.69 (0.05)	-	-
PD	3	6	67.67 (7.1)	81.0 (20.6)	1.66 (0.16)	36.13 (11.78)	2.39 (0.31)

3.1. Overall Effects of PD, Surface, and Slope

3.1.1. Spatiotemporal Parameters

The repeated measures MANOVA test performed on the spatial temporal parameters revealed that overall surface had a significant effect. Follow-up repeated measures ANOVA tests revealed that surface specifically affected the following dependent variables: speed ($p<.001$), cadence ($p=.004$), step length ($p<.001$), double limb support time ($p=.014$), and single limb support time ($p=.014$).

The following significant changes were observed from the flat to the irregular surface:

- Speed:
    - level condition: decreased ↓
    - cross slope: decreased ↓
- Cadence:
    - cross slope: decreased ↓
- Step length:
    - level condition: decreased ↓

3.1.2. Leg Kinematic Parameters

The repeated measures MANOVA test performed on the kinematic parameters revealed that overall surface and the medial/lateral position of a leg had significant effects. Follow-up repeated measures ANOVA tests revealed that surface specifically affected the following dependent variables: hip range of motion in the sagittal plane ($p<.001$), hip range of motion in the coronal plane ($p=.001$), hip range of motion in the transverse plane ($p=.007$), knee range of motion in the sagittal plane ($p=.006$), ankle range of motion in the sagittal plane ($p=.01$), and ankle range of motion in the transverse plane ($p<.001$).

Similarly, follow-up repeated measures ANOVAs also identified that the medial/lateral position of a leg specifically affected the following dependent variables: hip range of motion in the sagittal plane ($p<.001$), hip range of motion in the coronal plane ($p<.001$), hip range of motion in the transverse plane ($p<.001$), knee range of motion in the sagittal plane ($p<.001$), and ankle range of motion in the transverse plane ($p<.001$). The slope*limb position interaction specifically affected the following dependent variables: hip range of motion in the sagittal plane ($p<.001$), hip range of motion in the coronal plane ($p<.001$), hip range of motion in the transverse plane ($p<.001$), knee range of motion in the sagittal plane ($p<.001$), and ankle range of motion in the transverse plane ($p<.001$).

The following significant changes were observed from the flat to the irregular surface:

- Hip range of motion in the sagittal plane:
    - both limbs on the level condition: increased ↑
    - up-slope leg on the cross slope: increased ↑
- Hip range of motion in the coronal plane:
    - both limbs on the level condition: increased ↑
    - in the up-slope leg on the cross slope: increased ↑
- Knee range of motion in the sagittal plane:
    - both limbs on the level condition: increased ↑
- Ankle range of motion in the sagittal plane:
    - both limbs on the level condition: increased ↑
- Ankle range of motion in the transverse plane:
    - both limbs on the level condition: increased ↑
    - down slope leg on the cross slope: increased ↑
    - up slope leg on the cross slope: increased ↑

3.1.3. Trunk/Stability Parameters

The repeated measures MANOVA test performed on the trunk/stability parameters revealed that overall surface had a significant effect and follow-up repeated measures ANOVA tests revealed that surface specifically affected the following dependent variables: trunk range of motion in the sagittal plane ($p=.034$), trunk range of motion in the coronal plane ($p=.014$), and trunk range of motion in the transverse plane ($p=.022$).

The following significant changes were observed from the flat to the irregular surface:

- trunk range of motion in the sagittal plane:
    - level condition: increased ↑
- trunk range of motion in the coronal plane:
    - cross-slope: increased ↑
- trunk range of motion in the transverse plane:
    - level condition: increased ↑
    - cross-slope: increased ↑
- trunk COM acceleration RMS in the medial/lateral directions:
    - level condition: increased ↑
    - cross slope: increased ↑
- trunk COM acceleration RMS in the anterior/posterior directions:
    - level condition: increased ↑
    - cross slope: increased ↑
- trunk COM acceleration RMS in the vertical directions:
    - level condition: increased ↑

4. Discussion

From the main effects identified through the MANOVA, it appears that irregular surface (as defined in our study) had more of an effect than slope on the gait of both the healthy age-matched group as well as the group of participants with PD.

Overall the healthy age-matched participants walked more slowly and with shorter steps when walking on the irregular terrain, suggesting an effort towards maintaining a desired cadence from one surface to the other despite changes in other gait parameters. These parameters only exhibited significant change when comparing the surface types across a level slope. Irregular and uneven terrain studies on level ground have previously revealed similar strategies of adopting more conservative step patterns (Menant *et al.*, 2009; Thies *et al.*, 2005).

Overall across the level condition, surface only significantly affected ankle range of motion in the transverse plane. The height of the tallest cobblestone was nearly 4 cm, however the difference in heights of the stones was only 1-1.5 cm, therefore significant changes in step height may have been unnecessary to avoid tripping. Surface irregularities above 1.5 cm increase risk of ankle sprain injury and require compensatory strategies to prevent trips (Ottaviani, Ashton-Miller, & Wojtys, 2001).

Different increases in hip ranges of motion indicates that the cross slope resulted in asymmetric compensation strategies between limbs. Asymmetry has been described as being a means of creating and maintaining a functional leg length discrepancy to cope with the medial/lateral asymmetry of a cross-slope condition (Dixon & Pearsall, 2010). As significant changes across the surfaces on the cross slope involved the hip and were most asymmetric in the mediolateral directions, this suggests that the irregular surface mimicked/compounded the effects of mediolateral instability presented by cross slopes alone, further suggesting a surface*slope interaction.

Although the same parameters were significantly affected in the case of both groups in the same condition, the participants with PD were less affected. Their speed and step lengths reduced by a lesser percentage when introduced to the irregular terrain. Though these differences were not identified as being significant, it suggests those with PD were walking more conservatively across all conditions and made fewer gait adjustments to comply with the changing surface.

The results of this study will serve as a benchmark to observe if persons with PD adopt similar gait changes when walking in a virtual environment with smart shoes designed to provide realistic haptic sensations in VR gait. Furthermore, the changes observed in this study suggest that there are differences in biomechanics between healthy older adults and adults with PD when walking on irregular terrain. These differences require further study to develop appropriate training environments to improve gait and reduce fall risk.

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