GAIT MODIFICATIONS ON CHALLENGING TERRAIN: A STUDY OF PERSONS WITH PARKINSON DISEASE

by

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ABSTRACT

Persons with Parkinson disease (PD) are at risk for fall-related injuries as 60-80% of persons with PD fall annually. Basic treadmill training among other forms of exercise are used to combat the motor symptoms of the disease which help to precipitate the falls, however, such training often fails to prepare its patients to be able to navigate through more challenging environments. In order to improve upon this deficiency in training regimes, virtual reality (VR) has more recently been used to boost effectiveness. The University of Utah Treadport Active Wind Tunnel has been used for such VR rehabilitation in the past and current work is being done to improve upon the system. Therefore the purpose of this study was to characterize the gait of this fall-prone population on a combination of irregular surface and cross-slope conditions in order 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 during fall-prevention rehabilitation sessions in order to improve their effectiveness; 2) Provide biomechanical data that will be used to verify the ecological validity of the new VR training environment being created in the Treadport for use in PD rehabilitation research. The results of this study included that surface rather than slope was shown to have a more significant effect on the gait parameters of focus (i.e., spatiotemporal measures, lower limb 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 lower limbs joints (while only the ankle was affected in the case of the control group), and 3) increased trunk center of mass (COM) acceleration variability in all directions (suggesting a challenge to stability in all planes of motion). In the case of surface effect on gait when on a 10 degree cross-slope, the overall stability of the participants was more threatened than by the surface effect on the 0 degree slope.

Dedicated to my father and mother, Dr. Adrian Paul Hunt and Ann Kathleen Hunt, without whose love, support, faith, and infectious penchant for learning none of this would have been possible.

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CHAPTER 1

INTRODUCTION

1.1 Literature Review/Background

1.1.1 Parkinson Disease

1.1.1.1 Pathology

Parkinson disease (PD) results from a decrease in dopamine in the substantia nigra and the presence of Lewy bodies within the basal ganglia, brainstem, and cortex. The Lewy bodies in particular are thought to form as a result from an attempt to shield cells from toxic α – synuclein proteins. More Lewy bodies are associated with the extent to which the disease has progressed. The damages that these cause to the substantia nigra (i.e., one of the structures of which the basal ganglia is composed in between the brainstem and cortex) in particular is what has been thought to result in the motor impairments associated with the disease.[1]

Causes of these neural conditions have been linked to both environmental factors (which include exposure to toxins such as those found in herbicides) as well as genetic factors (which are thought to be related to only 10 to 15% cases).[2]

1.1.1.2 Epidemiology

Globally, PD is second only to Alzheimer's in prevalence as a neurodegenerative disease, as it reportedly affects roughly .3% of the industrial world.[3,4] It most commonly begins to affect patients when they are in their 60s and is more prevalent among men by a 3:2 ratio.[5] As it affects older adults, the fact that the global population is aging as a whole means that the presence of the disease will be even stronger.

1.1.1.3 Motor Symptoms

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.[1,2] Symptoms also include nonmotor effects including a loss of smell as well as sleep disturbance.[1]

1.1.1.4 Gait and Posture

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 lower limbs and nonzero velocity in the feet at the time of heel strike.[6] 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).[7] 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.[3]

1.1.1.5 Motor Symptoms Treatment (Pharmacological)

The most efficacious treatment is Levodopa, which acts to alleviate the effects of the disease via dopa decarboxylase (i.e., the process of converting Levodopa into dopamine in order to alleviate the deficit in the neurons).[1] The effects of the medication include a long and short response which are most effective when the treatment of Levodopa first begins. After the 'honeymoon period' (which usually lasts years) ends, then the effectiveness of the treatment fluctuates in what are termed on and off states.[7] Overall, Levodopa specifically improves the gait of its patients in that it helps to increase speed and step length, and it helps to reduce trunk forward flexion.[8,9]

1.1.1.6 Motor Symptoms Treatment (Nonpharmacological)

It is recommend that regular exercise routines be adopted as soon as one is diagnosed with PD and that such routines be maintained whether medications are initially sought out as well or not. Regular activity can help alleviate the degree of the rate of progress that the effect of the disease has on one's mobility, flexibility, an overall postural stability.[3]

1.1.2 Falls

1.1.2.1 Overview

Falls among the elderly are prevalent because of the balance and gait physiological impairments associated with aging. Medial-lateral stability challenge is especially associated with age (more so among the female population) and often leads to hip fracture.[10,11,12] Age factors beyond general instability that are associated with falling include reduced vision, peripheral sensation, lower limb strength and reaction time.[13,14] As many as 30% of community-dwelling older adults fall each year compared with 60-80% of persons with PD falling each year.[15,16] Persons with PD have particularly high fall risks in comparison to healthy-older adults because their gait is impaired both by factors associated with the disease as well as the aforementioned factors brought on by age (because PD most often effects older populations).[17]

1.1.2.2 Risk Factors

Approximately 70% of falls experienced by older adults take place during the task of walking[18,19], often resulting from an initial 'slip, trip, or loss of balance.'[20,21] 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).[18,22] 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 and is more likely to result in hip fractures than falls in other directions.[23,10] Hip fractures in turn result in greater likelihood of mortality.[12,19]

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.[24]

Additional risks include those which were identified through a questionnaire that was distributed as part one of this study. (See the methods section of this write-up for further details of the questions and resulting responses that were later used to identify the terrains to be used in part two/final part of this study. Among the risks identified were uneven terrain and cross-slope terrain, which is why the following sections discuss the biomechanics involved on both types of terrain.)

1.1.2.1.1 Gait On Uneven Terrain

Past studies involving irregular and uneven terrain have revealed a correlation between age and balance maintenance under such conditions.[25,26] Sensory and motor input impairments associated with aging populations have been identified in particular as causing balance challenges when navigating such terrain.[27-28] 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.[14,18,19,25,29] Others have emphasized an overall tendency for aged populations to tackle uneven terrain by overall adapting more conservative walking patterns which involve reduced speed and shorter steps.[25,26]

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 patients with PD.[30] In particular executive function (i.e., the use of past experience to dictate one's response to the present tasks) is important in being able to adapt one's gait well enough to safely navigate challenging environments. A well-documented symptom of PD is poor performance in executive functioning.[31] This explains the cognitive deficits which might contribute to the risk posed by such terrain to this population.

A search in PubMed yielded no studies focused on the gait of those with PD on irregular terrain, possibly because of the increased risk that these tests would seem to pose. However, because such terrain might significantly increase fall risk in this population suggests the need to identify more of the specific challenges that irregular terrain poses for those with PD. There is evidence that such challenges can be overcome through physical training.

1.1.2.2.1 Gait On Cross-Sloped Terrain

Very few studies exist regarding the biomechanics of navigating cross-sloped surfaces (i.e., surfaces sloped in the coronal/frontal plane), while multiple studies have focused on slopes in the sagittal plane.[32] Specifically, 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 most severe for these groups, it is beneficial to review the effects of lateral inclines on gait adaptations in this high risk population. This is especially true since such environments are common in real life situations and have been identified as specifically challenging in a questionnaire presented to persons with PD in a pilot study.[33] In Canada, cross-slopes in urban areas are recommended to be set at .5-2.3°; however, those slopes encountered are often cross-slanted up to 10°.[34,35]

The characteristic gait changes elicited by cross-slopes in comparison to control, level surfaces (as identified through past studies with healthy age-matched groups) include an array of differences. Even with smaller degrees of cross-slopes the resulting effect on gait can be significant. In general, in the sagittal plane, all lower limb kinematics are shown to be significantly affected by a slope and leg position effect, such that the down-slope lower limb joint angles are shown to exhibit overall decreased flexion and the up-slope lower limb joint angles are shown to exhibit increased flexion. In the coronal plane, significant changes are seen in the hip and ankle, with greater effects at the hip.[32]

In terms of the ankle motion, gait modifications include greater inversion in the down-slope ankle and greater eversion in the up-slope ankle. Cross-slope gait at the foot level has also been shown to include internal rotation of the up-slope ankle and a mostly neutral setting with a small degree of internal rotation in the down-slope ankle. It is thought that the rotation assumed in the up-slope foot may be a means of assisting in push off by allowing the foot to 'roll down the hill' and that the mostly neutral rotation of the down-slope ankle may be a strategy of keeping the center of mass (COM) from traveling downhill due to the deviation in its alignment caused by a slope in general.[36]

The difference in kinematics between limbs, especially in the sagittal plane suggests a discrepancy in overall functional length between them. Such discrepancies have been shown to be achieved mostly through pelvis obliquity, followed by knee and ankle changes in the sagittal plane. If pelvis obliquity specifically is not observed, it has been hypothesized that increased lateral trunk flexion is substituted instead.[32]

As slipping in mediolateral directions is a signature hazard on cross-slopes, good traction is important in navigating across them successfully. When navigating across a cross-slope, the resultant traction coefficient required during toe off and the traction components in the mediolateral directions throughout the entire gait cycle are larger than those required when walking across a level surface. In terms of the mediolateral traction, specifically, more lateral traction is necessary in the up-hill foot and more medial traction is necessary in the down-hill foot.[36] To avoid a fall, greater ground reaction forces are also requisite in the case of cross-slopes.[32] Significant increases in GRF between limbs and per limb between level and cross-slope conditions were reported by Dixon and Pearsall, who noted a 300% magnitude increase in the GRF in the down-slope limb.[32]

1.1.2.3 Fall Prevention Training/Physical Therapy

1.1.2.3.1 Overview

The basal ganglia, whose injury results in the depletion of dopaminergic cells that ultimately causes PD, is thought to exhibit a certain degree of plasticity.[37] For this reason, exercising results in combatting the progression of the gait effects of the disease and even improving upon pre-existing affects. Treadmill training, specifically, has been used in the past to effectively improve gait patterns more so than conventional physical therapy.[38]

1.1.2.3.2 Virtual Reality

It has been inferred that gait training involving higher intensity exercises as well as multisensorial feedback is much more effective for those with PD.[39,40] For this reason virtual reality (VR) has been integrated into exercise regimes in order to augment their efficiency. VR setups in past studies have involved a wide variety of setups including custom designs and commercial video game systems; overall these have been used more for stability-specific training rather than gait training. Overall these studies have shown that VR rehab environments are effective and that their effectiveness is transferrable to physical environments.[41,37]

1.1.2.3.2.1 Treadport Active Wind Tunnel

An example of a virtual reality training setup includes the University of Utah Treadport Active Wind Tunnel system which is an immersive virtual reality system consisting of a multiwalled projection setup and an advanced linear treadmill. Additional features which add to the realism of the environments projected by the system and which add to the variety of its applications as a whole include an active wind tunnel, a mechanical tether (for position and orientation measurement to control graphics and speed), and a system of partial weight support.[42-43] Among its applications, the Treadport has been used for gait rehabilitation research in the past. A study performed on it with people with spinal-cord-injury revealed that compared to traditional treadmill training, the Treadport environment had a more significant effect in improving several spatiotemporal and gait parameters.[43]

Among improvements currently being made to the system is the integration of 'Smart Shoes.' These will allow for the system's user to experience plantar haptic feedback in addition to all of the other multisensory features that the system already addresses.

1.2 Purpose/Aims

The aim of this study was to compare and characterize gait parameters (i.e., kinematic and spatial temporal) in different terrains in individuals with PD disease (PD) and healthy age-matched adults (HA). A combination of surfaces (i.e., flat and irregular) and cross-slope settings (i.e., 0 and 10 degrees) were evaluated. The overall goal of this study was to provide additional information to the body of knowledge that informs fall prevention and intervention programs. More specifically, these data will be used to develop a training program for individuals with PD in a virtual reality environment using the Treadport Active Wind Tunnel environment at the University of Utah (which is described in detail in the introduction section of this write-up).

As limited studies have been performed with persons with PD in different terrains because of associated fall risks, the predictability of the directional results of this study was low. Related studies involving different terrains and healthy age-matched groups as well as general gait studies of persons with PD were the basis of the indirect hypotheses in this study. The hypotheses are as follows:

- The gait of participants with PD will be different on the normal condition versus the irregular terrain and cross-sloped conditions.
- The gait of the healthy age-matched participants will be different on the normal

condition versus the irregular terrain and cross-sloped conditions.

- The gait of participants with PD will be different from the healthy age-matched participants on all slope/surface combinations.

The parameters used to address these hypotheses are discussed in detail in the methods section of this thesis. Overall they included groups of step, spatiotemporal, and lower limb kinematic parameters in order to identify strategies adopted to achieve postural control on each experimental terrain presented in this study. In addition, trunk kinematic and variability parameters were also measured in order to directly assess the degree of stability achieved through the gait adaptations identified.

CHAPTER 2

METHODS

2.1 Part One: Baseline Study – Identification of Terrains/Activities

2.1.1 Participants

In collaboration with Lorinda Smith in the Department of Physical Therapy at the University of Utah, eleven participants with mild to moderate PD (all males, 69.91±11.63 years old) were recruited for the initial part of this study. Their fall histories ranged from 0-50 falls and 2-365 near falls, with a median of three falls and twenty near falls in the past year. For the purpose of this study, a 'fall' was defined as a sudden, uncontrolled, unintentional, downward displacement of the body to the grounds 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.

Consent documents (see Appendix A) were signed by all participants prior to beginning any activities. All documents and procedures were approved in advance by the University of Utah Institutional Review Board.

2.1.2 Questionnaire

This part of the study consisted of obtaining information through a questionnaire that was to be used to identify environments and/or activities that pose stability challenges to persons with PD so that such elements could be integrated into the second part of the study. The questionnaire (see Appendix B), as drafted by Lorinda, included three sections: 1) difficulty of tasks and environmental factors, 2) outstanding challenges to stability or mobility, 3) fall history. The first section asked participants to use a 1-5 scale to rank the difficulty in maintaining balance in a list of environments and when performing a variety of tasks which were determined based on literature review, clinical screening tools, and Lorinda's clinical experience.[33] The second section asked more open-ended qualitative questions in order to better define what elements of the factors highlighted in section one made them more or less challenging in order to better define a hierarchy of difficulty with respect to maintaining stability. The third and final section was then used to inquire about the specific details of the fall history of the participants in the past year in order to draw patterns between their responses in sections one and two with personal experiences encountering fall risk elements.

2.1.3 Questionnaire Results

The limitations from the questionnaire distribution part of this study included the size of the sample and that only males from a small geographic area were recruited. The overall results of the questionnaire are highlighted in Figure 2.1 – Figure 2.4.[33] The questionnaire revealed that uneven surfaces were at the top of the hierarchy of perceived difficulty (as shown in Figure 2.1), even though such surfaces had not initially been rated at a level as high as some other factors when the factors were evaluated separately

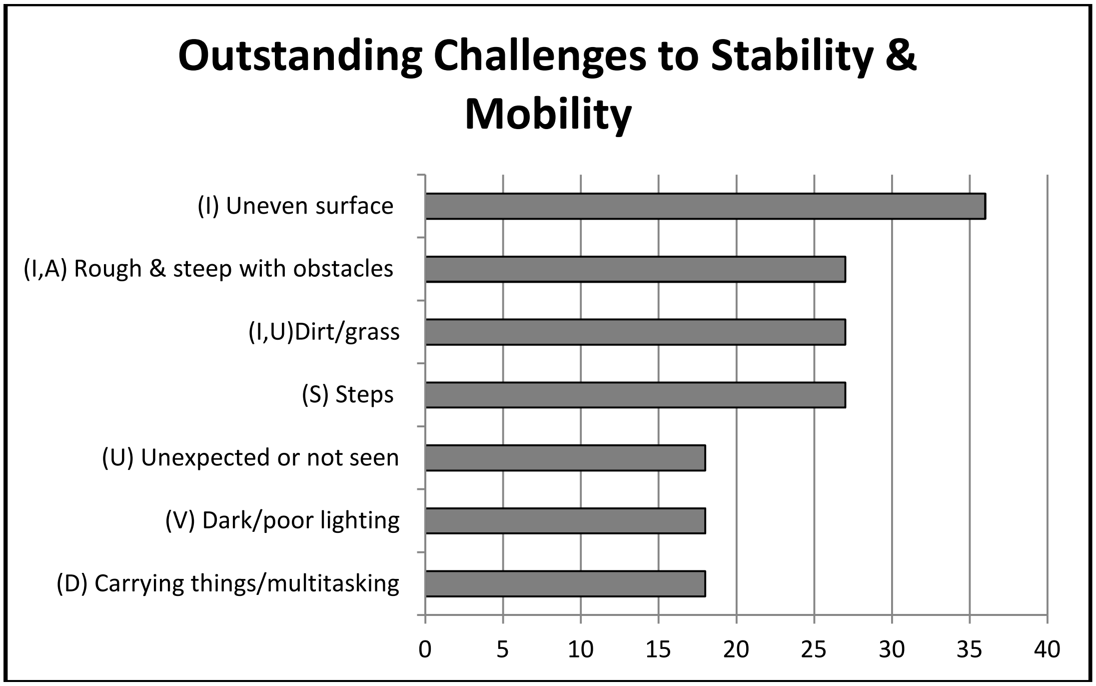


Figure 2.1. Greatest Challenges to Stability. Note: The horizontal axis represents the percentage of participants who identified each element.

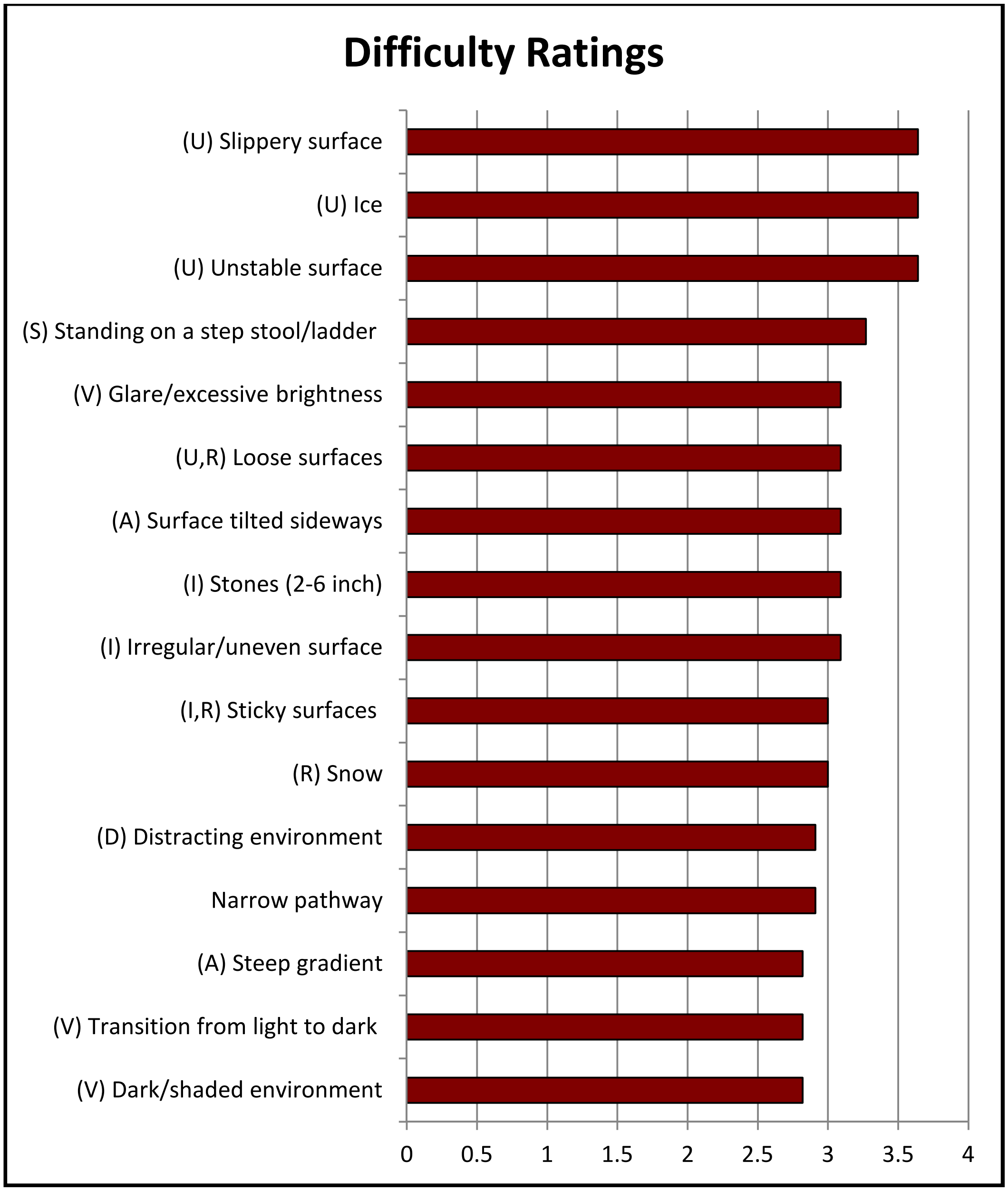


Figure 2.2. Balance Difficulty Ratings. Note: Based on Likhert scale of 1 to 5.

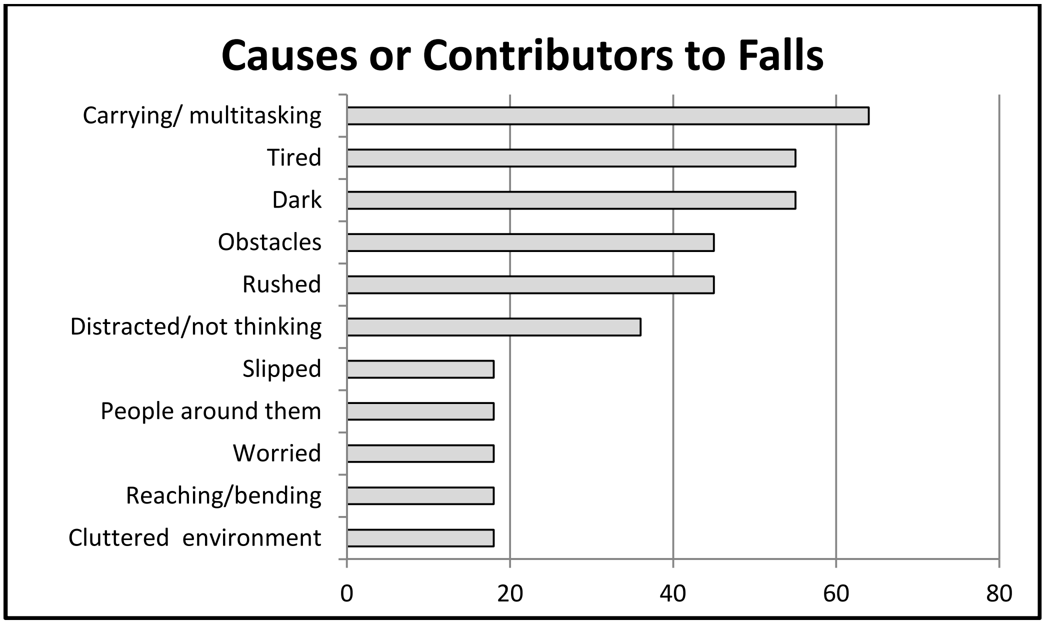


Figure 2.3. Fall-Contributing Elements. Note: Horizontal axis represents percentage of participants who identified each element.

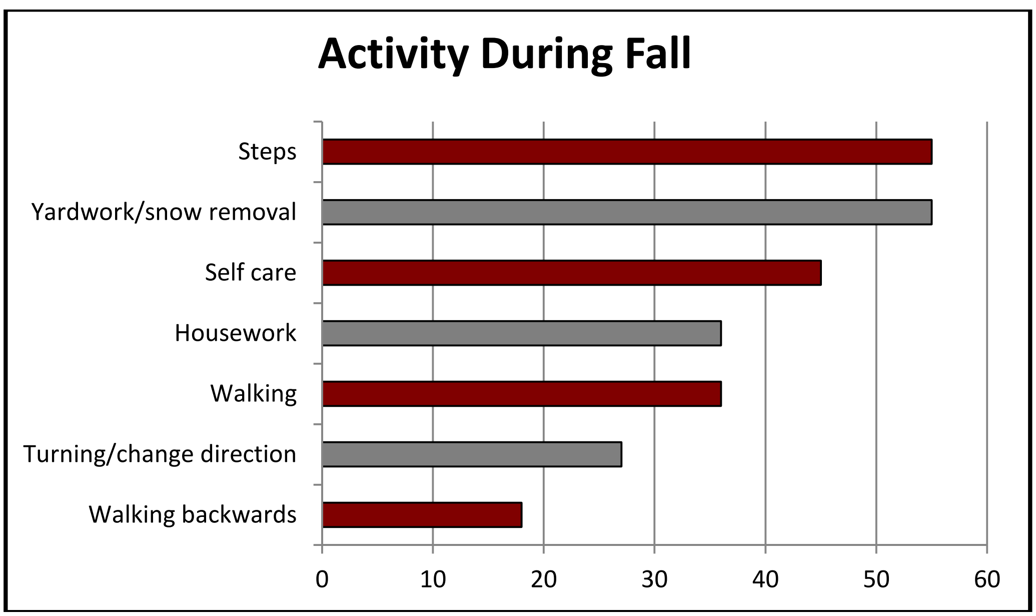


Figure 2.4. Top Fall Risk Activities. Note: The horizontal axis represents the percentage of participants who identified each element.

(Figure 2.2). In addition, the questionnaire revealed that, in general, tasks and/or additional environmental elements rather than certain surfaces were more often the cause of actual falls that the participants had experienced. The specific top contributor in these real life cases was identified as the activity of carrying or general multitasking (as shown in Figure 2.3) and the activity when performed by itself that most often caused falls was identified as climbing stairs (Figure 2.4).

The combination of these results as well as the limitations set by the VR environment and the Smart Shoes were used to determine the final terrains and activities that would first be tested in physical mockup setups. The Ergonomics and Safety lab in the Mechanical Engineering Department as well as in the Mocap lab in the Physical Therapy Department were used to house these mockups. The tasks tested in the Mocap lab included obstacle negotiation as well as dual-tasking, where the dual task included a cognitive task in which the participants were asked to discuss their opinions on a pre-selected subject matter. The Ergonomics and Safety lab mockups, which are those that are described in this thesis write-up, included a combination of off camber surfaces tilted in the frontal plane, uneven terrain consisting of cobblestones, and dual-tasking in which the dual task was a cognitive test involving arithmetic.

2.2 Part Two: Application of Baseline Study Results – Biomechanical Analysis

2.2.1 Participants

Study participant demographics included: nine patients with PD and nine healthy age-matched controls (see Table 2.1 for demographic info). (Ten healthy young controls were also recruited, although their data are to be used for future analysis). A combination

Table 2.1. Participant Demographics.

Group	*# Females*	*# Males*	*age*		*weight (kg)*		*height (m)*		*UPDRS score*		*H&Y score*	
			mean	***s.d.***	***mean***	***s.d.***	***mean***	***s.d.***	***mean***	***s.d.***	***mean***	***s.d.***
HA	4	5	67.67	8.03	74.49	5.56	1.69	0.05	-	-	-	-
PD	3	6	67.67	7.05	80.98	20.58	1.66	0.16	36.13	11.78	2.39	0.31

of hardware and software issues (described in more thorough detail in the gait assessment section) resulted in the collection of some unusable data as well as a delay in data collection that lapsed multiple months. Due to these issues, the participant populations were somewhat smaller than the goal population size of n=10 per group.

Participants were recruited from the University of Utah campus, where the participants with PD more specifically were recruited from the Rehabilitation and Wellness Clinic in the Physical Therapy Department. Healthy age-matched participants met the following criteria: 1) 50 years of age or older, 2) Have no balance problems, 3) Have no medical condition or injury that might affect his/her ability to participate. Also, those with PD met the following exclusion criteria: 1) Have PD, but are not so incapacitated by the disease that they require the use of a mobility aid (i.e., H&Y score of II-III), 2) 50 years of age or older, 3) Have no other medical condition or injury that might affect his/her ability to participate, 4) Have not had a deep brain stimulator implanted.

Consent documents were signed by all participants prior to beginning any activities. All documents and procedures were approved in advance by the University of Utah Institutional Review Board.

2.2.2 Mockup Environments

Two 40cm x 60cm force plates (Bertec, Columbus, OH, USA) were imbedded to be flush with the surface of a raised .76 m x 7.3 m walkway. The walkway (which was originally constructed for another gait study) was built such that it was supported by a series of five jacks (see Figure 2.5) on either side so that it might mimic a cross-slope condition. Uneven terrain was simulated by modifying polyurethane faux rock panels purchased through FauxPanels.com. The sections of the panels that fell over the force plates were cut separately from the bordering sections of the panels in order to prevent the transfer of force to the force plates during gait events occurring outside of the boundaries set up by the force plate edges (see Figure 2.6). The panels were affixed to the walkway through screwing them into the wooden walkway frame and taping those which covered the force plates so that they could be easily removed between flat and irregular terrain conditions per trial. In total, three surface/slope conditions identified as being difficult from the questionnaire were simulated with this walkway setup in addition to a control flat/level condition (see Figure 2.7). These 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 faux panels was then used a control condition.

In order to minimize risk of injury during the trials, fall protection elements were integrated into the experimental setup (see Figure 2.8). The elements included railing constructed per OSHA standards (despite the walkway being low enough that it is exempt from railing regulations), stairs constructed per OSHA standards, and an overhead protection system. The overhead system was designed by PhD candidate Robin Elliott such that it would prevent a maximum fall force of 1800 lbs. as stipulated by OSHA.

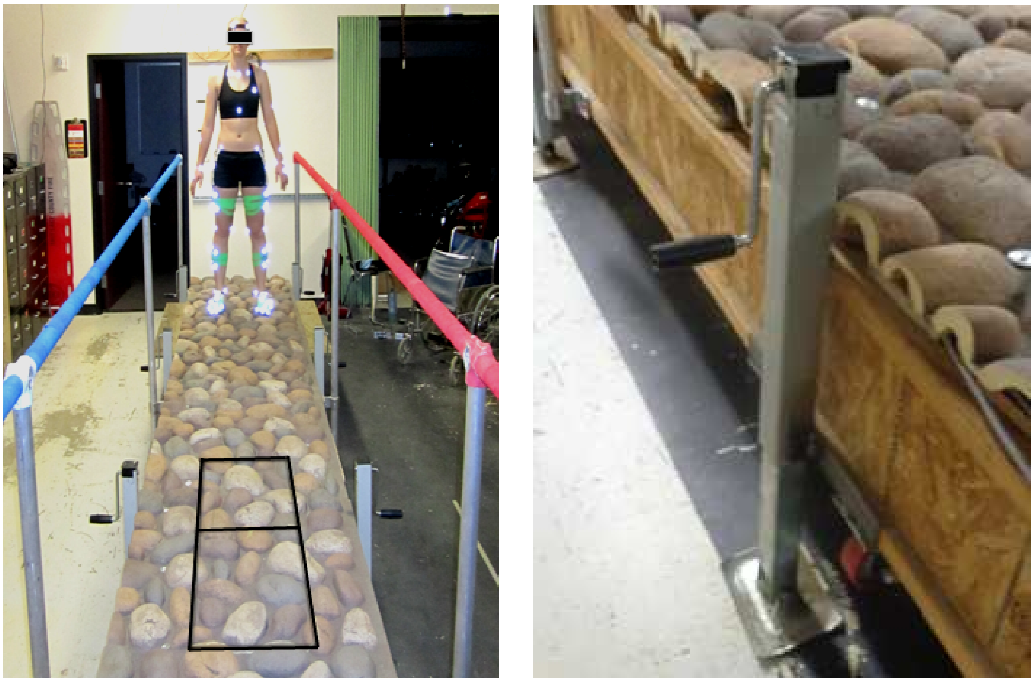


Figure 2.5. Walkway And Supporting Jack. Note: The walkway as pictured is set at the irregular/0_degree condition. Also note the participant pictured here was one of the healthy young participants recruited for data to be used in future analysis and was given the option not to use the overhead fall protection system).

Figure 2.6. Imbedded Force Plates.

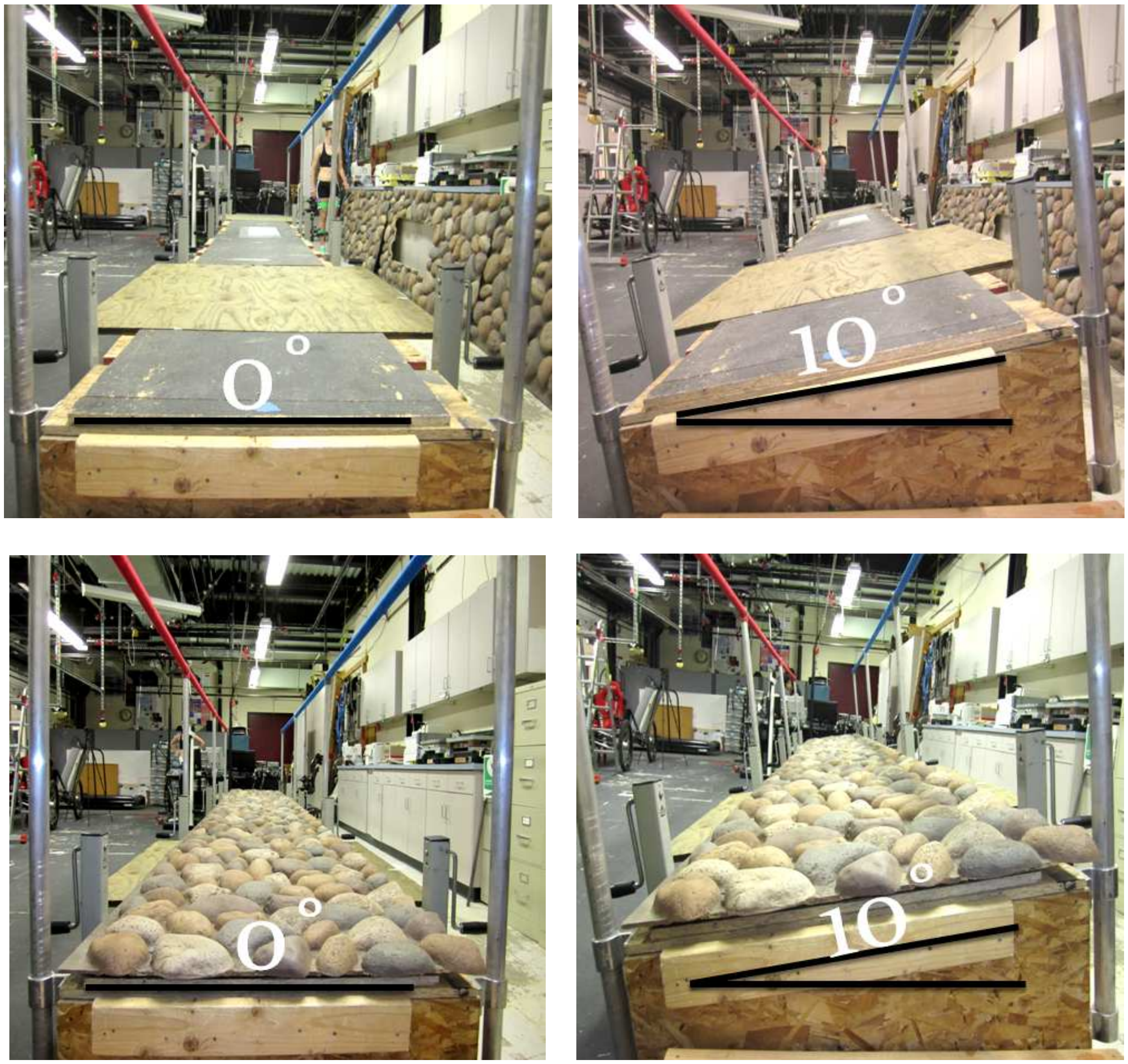


Figure 2.7. Four Surface/Slope Test Conditions.

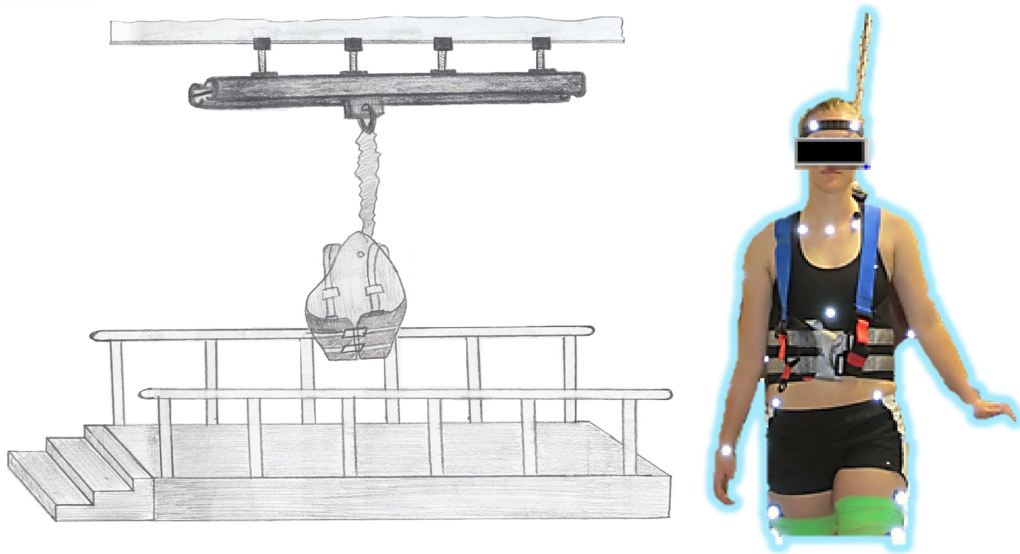


Figure 2.8. Fall Protection System Components. Note: The sketch (created by and used with the kind permission of Raunaq Srivastav) depicts overhead protection system, safety railing, and stairs constructed around the original walkway as a safety precaution for this study. Picture: healthy young pilot participant wearing fall protection safety harness.

Using the equation presented by Nigel Ellis in 'Introduction to Fall Protection,' it was determined that the maximum force that might be felt by a 300 lbs. person attached to the system would be 756 lbs., which met the aforementioned design requirement. The final fall protection system design consisted of a double Unistrut beam hung from the ceiling such that it was centered and parallel to the length of the walkway. A carriage/trolley system inserted in the channel of the beam was connected to a rope that was then clipped onto the safety vest of the participants. The tether was adjusted per participant in order to ensure that if each participant were to fall, that they would avoid falling far enough to make contact between their knees and the walkway surface. As the primary element in the fall protection setup, the overall integrity of the overhead protection system was analyzed via system safety analysis using the following assessment techniques: fault tree analysis (FTA); failure mode, effects, and criticality analysis (FMECA); and operating and support hazards analysis (O&SHA). (See assessment results in Appendix C)

2.2.3 Trial Procedures/Walking Protocol

Walking trials were performed on each condition at self-selected speeds and, in the case of participants with PD, commenced one hour after taking anti-Parkinsonian medication in order to ensure an 'on' state during the activities. A single trial was defined as the completion of walking across the full length of the walkway in one direction. The order of the conditions encountered per participant was randomized using an Excel randomizer blocked on the degree of camber of the walkway. Single tasks and dual tasks were performed on each condition and the order in which they were performed was also based on an Excel randomizer. Each condition and task was maintained for a series of trials until three 'successful' trials were completed so that an average of the data from the three trials could be used to establish a better estimation of normal gait patterns in that specific combination of circumstances. A 'successful' trial was defined as that which involved the following event on each force plate: a heel strike by a foot as it was isolated on the specific force plate on which the strike occurred. In order to achieve 'successful' trials without having patients adjust their gait, specific starting lines were established per participant per condition. To dissuade participants from the temptation to still try and adjust their gait to ensure 'successful' trials every time, they were asked not to look at their feet unless they would normally do so when encountering examples of the terrains and tasks being presented to them in the real world.

All trials were performed at self-selected speeds in order to make the collected data more representative of a real life encounter with such conditions and in order to specifically analyze the speeds chosen between conditions because decreases in speed would be informative in that they might indicate a fear of falling.[21]

Following the completion of all of the trials, participants were asked to fill out a questionnaire primarily focused on gauging how challenging the participants ‘thought’ the terrains were in terms of stability maintenance in order to compare their perceptions with the level of challenge displayed in their gait patterns.

2.2.3.1 Dual-Task Details

As dual tasking was identified as a fall risk in addition to uneven terrain via the questionnaire, this was also implemented into the experimental procedure. The addition of the dual tasks was meant to add additional challenge to the gait tasks in case the irregular and cross-slope elements did not present enough of a stability challenge in themselves. A certain degree of challenge was sought out because the VR environment that is to be set up to mimic the conditions represented in this study will be used to improve the gait of participants with PD and improvements can only be made through testing/significantly challenging their preliminary abilities.

A cognitive task was selected for the second task because there is a growing body of evidence linking cognitive function to gait and thus it was assumed that a cognitive task would suffice as well as an additional physical task to add difficulty to the primary gait task.[44] The specific cognitive task used was serial 7 subtractions. The task involved selecting a starting number using an Excel randomizer and then asking participants to perform subtractions of 7 as many times as they could from that initial number before reaching the end of the track where the trial would end. For every trial on every terrain condition, the randomizer was used to select a different starting number in order to prevent learning effect bias between trials. Serial 7 results were recorded using a wireless audio transmitter and receiver (Shure Brothers Inc., Chicago/Niles, IL, USA) and Audacity® audio recording software.

The effects of the dual task were not among the focus of this write-up, but future work involving these data is planned.

2.2.3.2 Posttrial Questionnaire Details

The posttrial questionnaire (see Appendix D) consisted of questions which focused on two primary topics: 1) participation-related questions and 2) general fall history questions. The first section asked participants to use a 1-5 scale to rank the difficulty in maintaining balance while ambulating on each of the surfaces presented to them in this study when performing the single versus the dual task. In addition, more open-ended qualitative questions were also asked concerning their experience in the lab environment. The second section was only given to the participants with PD and was similar to that concerning fall history that was issued in part one of the study. As the participants in part two of this study were not the same individuals who were seen during part one, this section was used primarily to assess the overall health of the new group of participants in comparison to those from part one who initially identified the fall risk environments that were used in part two.

2.2.4 Gait Assessment

In order to collect movement data, motion capture equipment was integrated into the experimental setup. Video data was collected at 100 Hz through the use of Capture2D (C-Motion, Germantown, MD, USA) and 24 - V100:R2 cameras (NaturalPoint, Corvallis, OR, USA). The original camera setup included only 16 cameras, but poor coverage (as gauged by processing time) led to the recreation of the capture volume in order to accommodate the final set of 24. This resulted in a larger delay in data collection than was anticipated due to software and hardware issues that were discovered during the process of expanding the system. These additional issues resulted in the inability to get all of the 24 cameras to properly function at the same time. The specific software defects contributing towards the erred calibrations were determined through collaboration with the software's support team, who discovered a maximum camera capacity issue. The specific hardware defects were then determined through the process of failure mode analysis, which resulted in the discovery of an overly-taut cable as well as usb driver/port overload issues.

A total of 76 markers were included in the static marker set. During dynamic trials markers on the most proximal and distal ends of the feet were removed due to the likelihood that they would be knocked off during the negotiation of the uneven, cobblestone condition. Medial markers were left on during the duration of all trials so that they could be used as backup tracking markers, unless they were found to affect the gait of a participant. Note that 12 markers were used to define each foot, though the foot model used in the final assessments was a single segment. Participants were dressed in tight fitting clothing and wore athletic shoes of their choice. Markers were adhered to the participants via double-sided tape and clusters of markers were adhered via coflex tape. The placement of all of the markers can be seen found in Appendix E.

Two full gait cycles were used for the use of overall spatiotemporal, trunk/stability, and kinematic calculations. One step on each of the two force plates was then used for the purpose of inverse dynamic calculations for kinetics. Force plate analog data were collected and synched with the video data using NI LabView (National Instruments Corp., Austin, TX, USA) software.

Data were processed and calculations were performed using AMASS (C-Motion, Germantown, MD, USA) and Visual3D (C-Motion, Germantown, MD, USA). Based on recommendations made by Winter (and following the signal processing protocol used by previous studies involving the same motion/force system in this researcher's lab), video and analog data were filtered with a fourth-order low-pass Butterworth filter at 6Hz and 20Hz in order to reduce noise in the signals.[53]

2.2.4.1 Spatiotemporal Parameters

In trials in which the force plate data were clean, gait events over the force plates were determined with force plate signals while the events off the force plates were based off of an algorithm based off of patterns established by the force plate events as available through the 'Automatic_Gait_Events' function available in Visual3D (C-Motion, Germantown, MD, USA). Those trials in which the force plate data were unusable due to various reasons, gait events were based off of kinematics only. As recommended by Zeni's coordinate based algorithm, which was tested on gait impaired populations, the kinematic-only defined events were determined from the distance of feet markers from the pelvis.[54] The maximum distance between a heel marker and the pelvis (when the foot marker was anterior to the pelvis) defined heel strikes and the maximum distance between a toe marker and the pelvis (when the foot was posterior to the pelvis) was used to define toe offs. Once all of the events were marked, the spatiotemporal parameters were calculated.

As aforementioned, medial-lateral stability challenge is associated with age.[10] Step width is often modified as a means of combating this challenge because it increases one's base of support in the frontal plane; therefore in the past step width has been the focus of irregular terrain studies with older participants, as well as with healthy aged adults with motor disabilities similar to PD such as peripheral neuropathy.[45,29,46] Furthermore, gait/step variability is associated with fall risk, so step width variability has been used to assess balance control in older adults when faced with irregular terrain studies as well.[29] In addition, gait speed is among the gait parameters that have been associated with PD in general (along with step width/length) and it is also linked to age.[29] Due to the use of all of these parameters in past related studies, these parameters in addition to general gait parameters were the spatiotemporal parameters of focus in this study.

Overall, the spatiotemporal parameters that were analyzed in this study included the following:

- 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.[47]

2.2.4.2 Lower limb Kinematic Parameters

Due to the asymmetry involved in gait on off-camber surfaces, lower body kinematics and the resulting functional leg lengths resulting from their adaptations have been reviewed in past studies involving such conditions (which up to this point have only included healthy young subjects).[32,34] Kinematic parameters were of particular interest/concern in this study not just because of their centralization in such past studies, but also because joint inflexibility is an effect of age and is exacerbated by PD.[48]

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

- 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)

2.2.4.3 Trunk/Stability Parameters

A majority of the mass of a person exists in the trunk and thus general trunk kinematics play a large role in maintaining stability. In addition, as visual input is important in planning one's movement and stabilization of the head is requisite to trunk movement,[49] trunk center of mass acceleration variability is also associated with balance control (interstride trunk acceleration variability but not step width variability can differentiate between fit and frail older adults) and has thus also been used in irregular terrain studies in the past.[25] As such, trunk-related measurements were used as the more direct measures of stability in this study.

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 center of mass (COM) acceleration root mean square (RMS) (i.e., the more direct measures of stability selected for this study as measured anterior/posterior, medial/lateral, and vertically)

Trunk COM acceleration variability was normalized to gait speed as done in past studies.[25] (In addition, it should be noted that although ground reaction forces and kinetics are a major part of stability on off-camber surfaces navigation because of the need to maintain a certain degree of mediolateral ground reaction forces in order to avoid slippage, [32] these were not the focus of this study because the Treadport VR environment which will be verified with this study's results does not have ground force measurement capabilities.)

2.2.5 Statistical Analysis

Study parameters were grouped into spatiotemporal measures, lower limb kinematic measures (which included functional leg length because it is directly 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. up-slope 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. In order to further investigate significant effects revealed via the MANOVA tests, the MANOVAs were followed up with repeated measures ANOVAs and then pairwise post hoc tests. In order to avoid accumulated type I error due to the multiple pairwise tests, Bonferroni corrected p-values were used for final assessments. Corrected p-values were calculated by dividing each parameter's p-value by the number of dependent variables within the MANOVA test of focus (i.e., eight variables in the case of the kinematics group test, seven in the case of the spatiotemporal group test, and six in the case of the trunk/stability group test). As the hypotheses were nondirectional, the reported p-values were based off of two-tailed test results. Matlab (R2014a, The Mathworks Inc., Natick, MA, USA) was used to format gait data exported from Visual3D (C-Motion, Germantown, MD, USA) and SPSS (Version 20 for Windows, SPSS Science, Chicago, USA) was used to perform the final statistical analyses.

CHAPTER 3

RESULTS AND DISCUSSION

3.1 Results

3.1.1 Descriptive Statistics

3.1.1.1 Spatiotemporal Parameters

In general, there was a between group trend of consistently higher speed and step lengths among the healthy age-matched participants in comparison to the participants with PD (see Table 3.1 and Figure 3.1 – Figure 3.7). Speed and stride length differences between such groups have been identified as hallmark examples of the effects of PD on gait because even in early stage PD and in the 'on' state (i.e., when PD medication is effectively treating motor symptoms, versus the 'off' state which occurs when the effects of the medication begin to wear off), those with PD have an 'internal inability' to achieve normal step lengths and thus normal speeds.[50] Furthermore, past studies have revealed a significant correlation between increased speed and increased stride length with better dynamic balance in persons with PD. In the case of the group of participants with PD, the cross-slope with an irregular surface, followed by the level irregular condition and then the flat cross-slope condition, elicited the smallest speed and step length to the highest suggesting that the same order of conditions might also represent the ranking of conditions from most challenging to dynamic stability to least challenging.

Table 3.1. Spatiotemporal Parameters - Descriptive Statistics.

		Flat Surface				Irregular Surface			
		0 deg Slope		*10 deg Slope*		*0 deg Slope*		*10 deg Slope*	
GROUP	**Parameter**	***mean***	***s.d.***	***mean***	***s.d.***	***mean***	***s.d.***	***mean***	***s.d.***
HA	***Speed***	1.12	0.28	1.08	0.29	1.00	0.32	1.02	0.34
	cadence	100.73	9.46	100.72	11.25	96.33	15.22	98.68	15.79
	step w	0.14	0.02	0.14	0.03	0.15	0.02	0.14	0.02
	step l	0.83	0.15	0.79	0.15	0.76	0.17	0.77	0.18
	step wV	0.04	0.01	0.03	0.01	0.05	0.01	0.04	0.01
	single support time	0.76	0.09	0.76	0.09	0.73	0.12	0.74	0.12
	double support time	0.24	0.09	0.24	0.09	0.27	0.12	0.26	0.12
PD	***Speed***	0.95	0.19	0.97	0.22	0.86	0.23	0.84	0.26
	cadence	96.18	8.73	97.93	10.42	91.88	12.80	90.54	13.71
	step w	0.15	0.03	0.16	0.04	0.16	0.03	0.16	0.04
	step l	0.76	0.11	0.75	0.11	0.71	0.11	0.70	0.15
	step wV	0.03	0.01	0.04	0.01	0.04	0.02	0.04	0.01
	single support time	0.74	0.07	0.72	0.08	0.71	0.09	0.68	0.11
	double support time	0.26	0.07	0.28	0.08	0.29	0.09	0.32	0.11

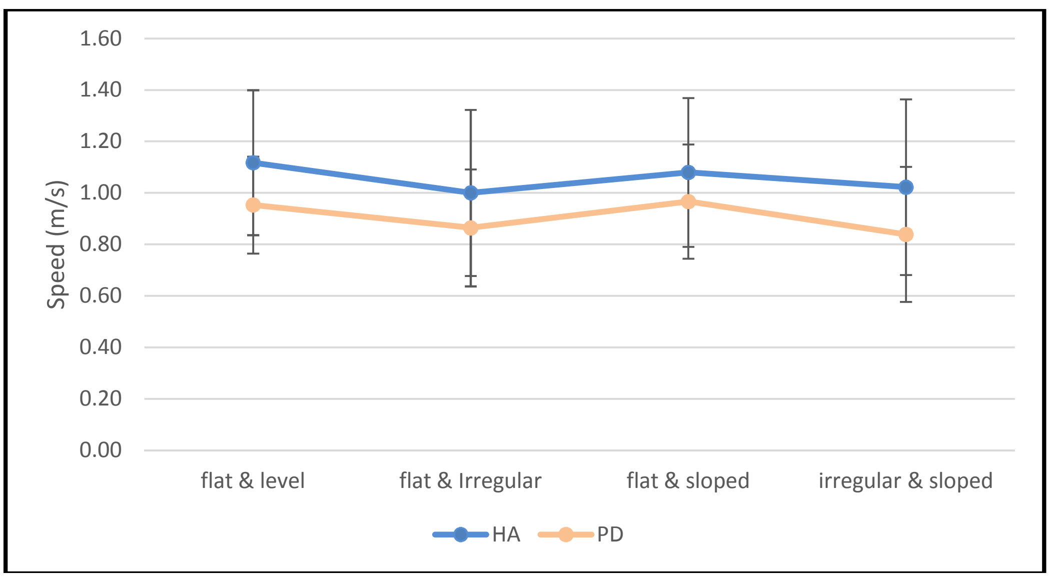


Figure 3.1. Mean Speed Per Condition.

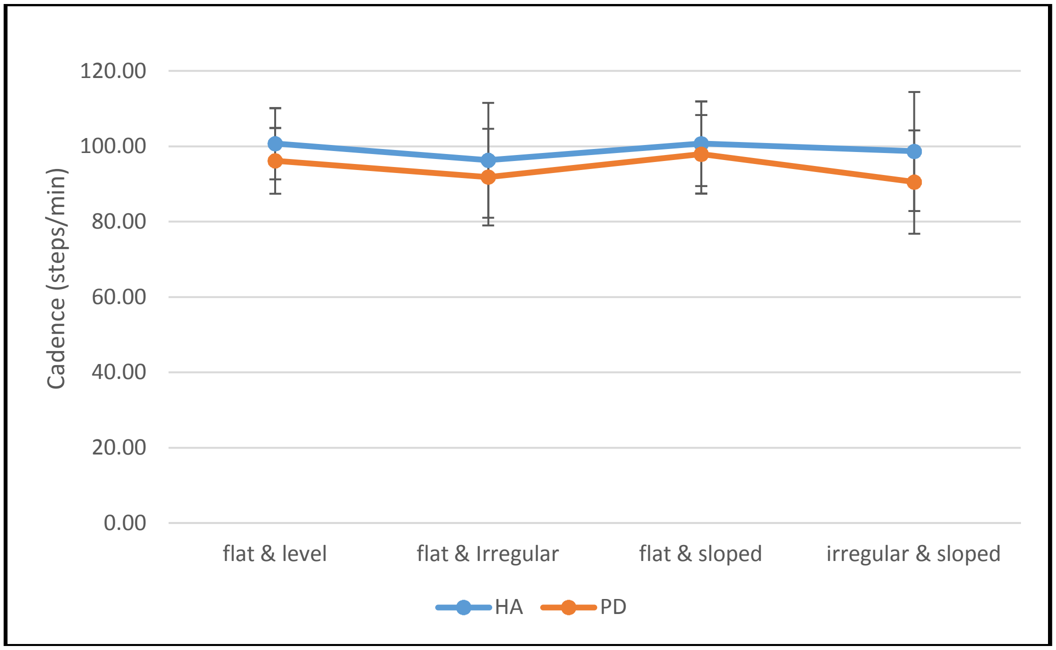


Figure 3.2. Mean Cadence Per Condition.

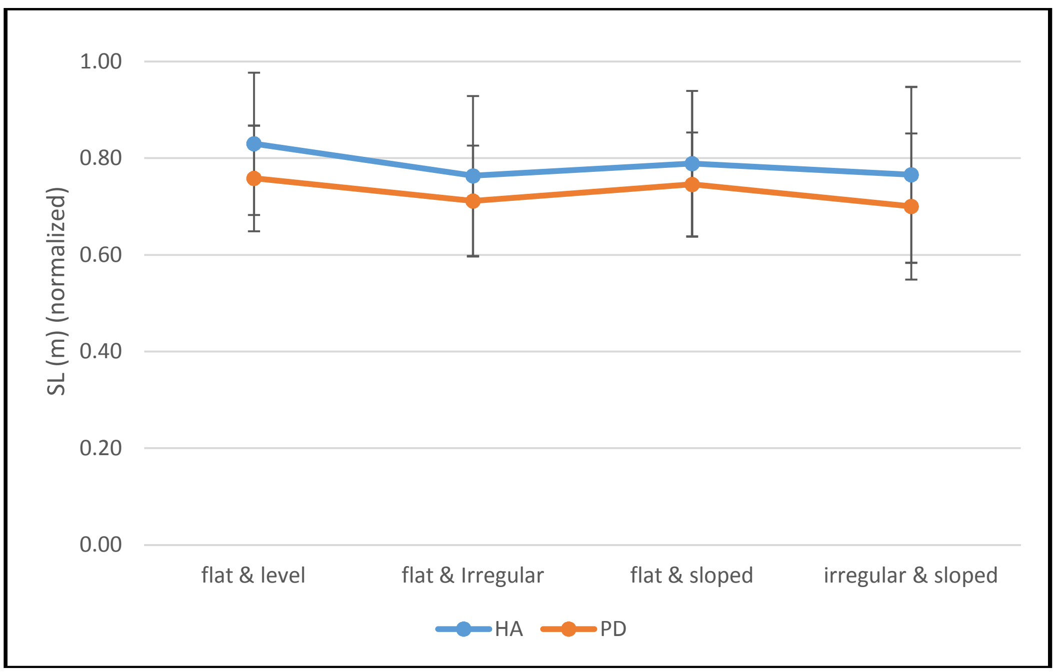


Figure 3.3. Mean Step Length Per Condition.

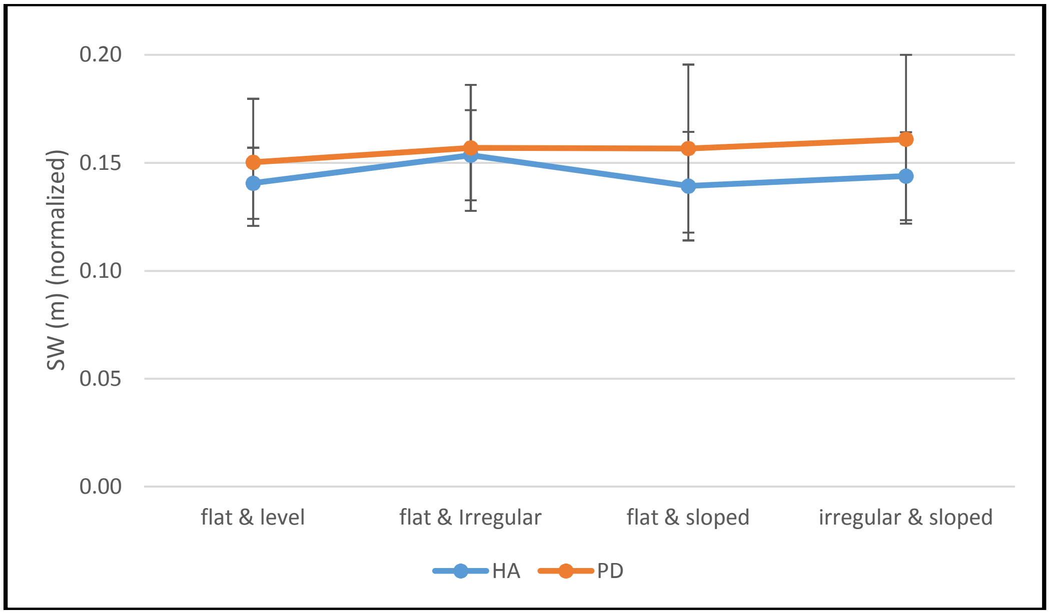


Figure 3.4. Mean Step Width Per Condition.

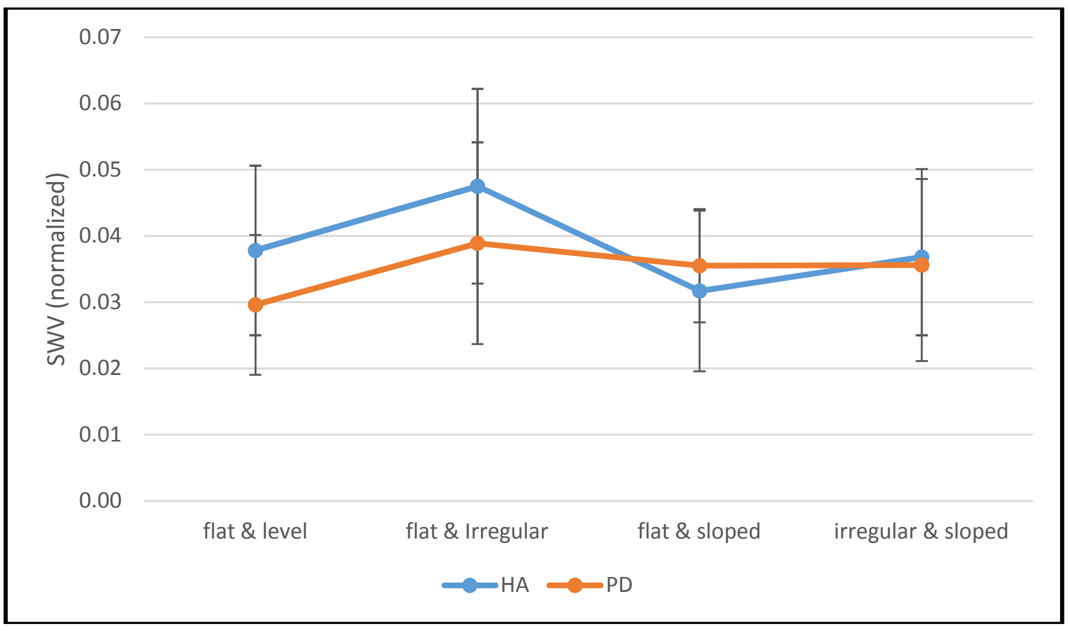


Figure 3.5. Mean Step Width Variability Per Condition.

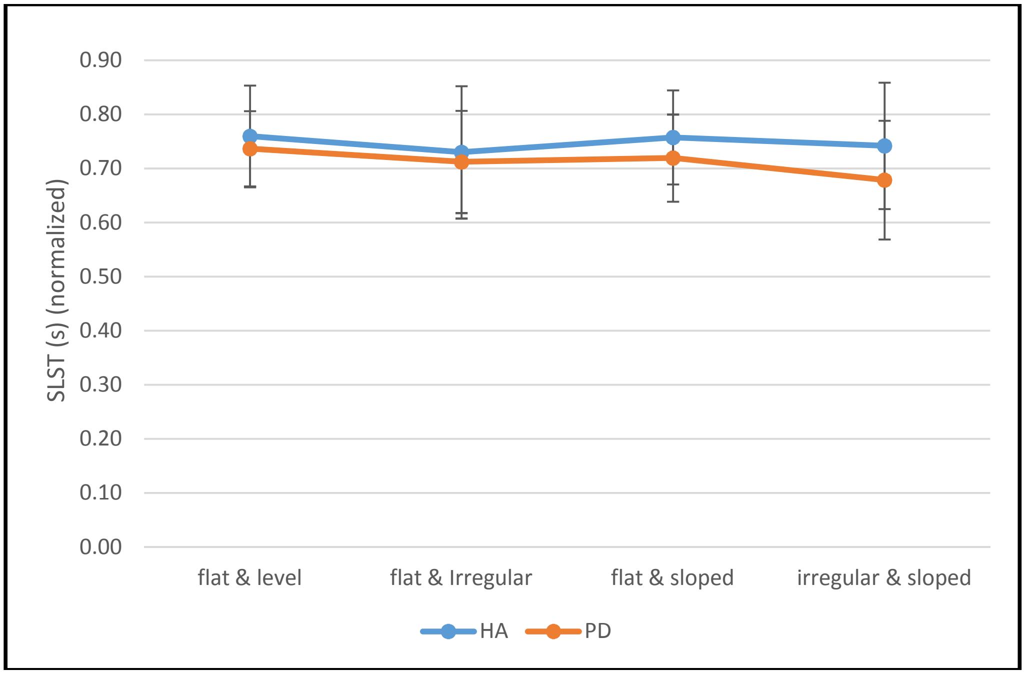


Figure 3.6. Mean Single Limb Support Time Per Condition.

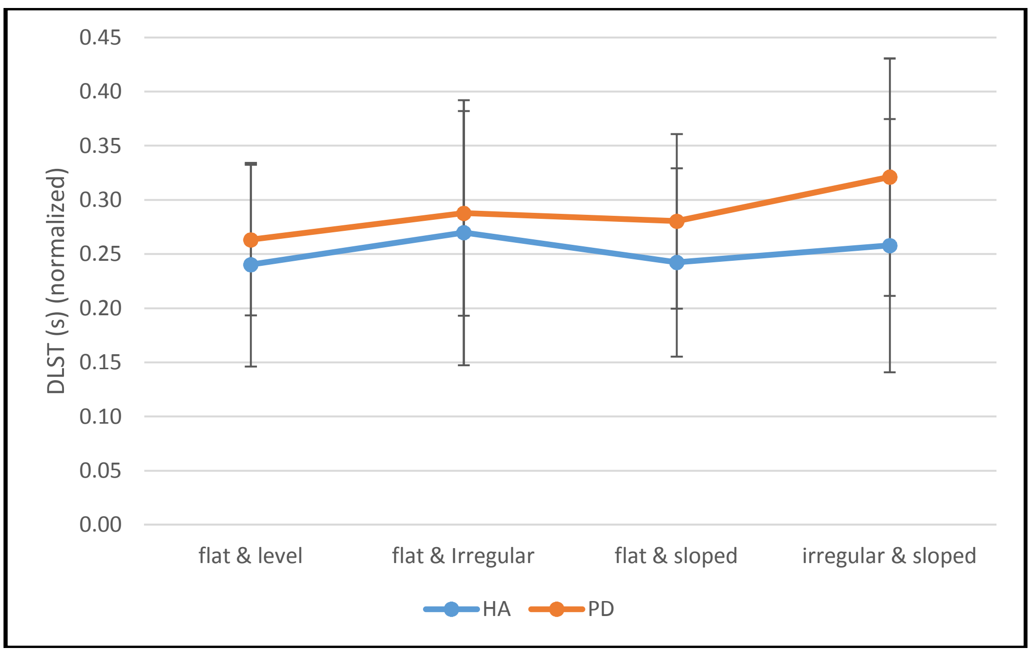


Figure 3.7. Mean Double Limb Support Time Per Condition.

3.1.1.2 Lower Limb Kinematic Parameters

Overall the trends exhibited by each group were similar between the surface and slope conditions in terms of joint angle motion (see Table 3.2 and Figure 3.8 – Figure 3.15), which support the RM MANOVA results (described in proceeding sections) that no overall group effect was present. However there were some parameters which indicated a greater difference as a result of group type that are worthy of mention: the healthy age-matched group showed a drastically greater change in the up-slope leg coronal plane ankle range of motion from the flat cross-slope terrain to the irregular cross-slope terrain and there was a great deal more variability in hip range of motion in the coronal plane between all conditions for the healthy age-matched group than for those with PD.

3.1.1.3 Trunk/Stability Parameters

As shown in Table 3.3 and Figure 3.16 - Figure 3.21, each parameter increased with the addition of surface irregularity (albeit not significantly in every case) whether it be on a level or cross slanted surface, such as the case with a past study with healthy young and healthy age-matched adults involving irregular terrain as well.[25] Comparing group trends on irregular surfaces, larger trunk range of motion in the sagittal and transverse planes were seen in the case of those with PD while greater mediolateral range of motion was exhibited by the healthy age-matched participants. Furthermore, on irregular surfaces those with PD exhibited a greater vertical and mediolateral trunk COM acceleration RMS, while the healthy age-matched group exhibited higher trunk COM acceleration RMS in the anteroposterior directions. In terms of the control condition, the conditions without irregularity, the healthy age-matched participants had higher values for all of the

Table 3.2. Lower Limb Kinematics - Descriptive Statistics.

		Flat Surface						**Irregular Surface**					
		0 deg Slope		***10 deg Slope***				***0 deg Slope***		***10 deg Slope***			
		Either Leg		***Down-slope Leg***		***Up-slope Leg***		***Either Leg***		***Down-slope Leg***		***Up-slope Leg***	
GROUP	**Parameter**	***mean***	***s.d.***	***mean***	***s.d.***	***mean***	***s.d.***	***mean***	***s.d.***	***mean***	***s.d.***	***mean***	***s.d.***
HA	***hip (sagittal)***	44.46	6.01	43.19	5.88	44.67	6.13	46.60	5.10	44.74	6.02	48.41	6.86
	hip (coronal)	11.68	1.97	10.17	2.21	12.07	2.77	12.48	1.95	12.00	2.49	12.51	2.60
	hip (transverse)	14.12	2.95	14.70	1.76	13.27	2.58	15.59	3.40	16.01	3.98	14.78	3.36
	knee (sagittal)	66.25	5.43	63.30	4.77	68.09	7.10	68.80	9.77	64.77	8.77	70.62	8.51
	ankle (sagittal)	28.97	4.14	30.70	4.59	30.66	2.67	32.10	3.71	31.70	3.38	34.04	4.27
	ankle (coronal)	16.47	2.65	16.81	3.48	15.26	3.02	17.90	3.17	18.42	4.63	19.20	6.02
	ankle (transverse)	13.90	3.65	13.12	3.04	18.46	4.00	23.21	5.67	21.42	3.21	25.64	5.17
	functional leg length	1.00	0.00	0.96	0.08	0.93	0.08	1.00	0.00	0.97	0.09	0.95	0.09
PD	***hip (sagittal)***	42.36	6.07	43.23	5.16	45.52	6.03	45.38	5.33	44.91	5.72	47.72	5.63
	hip (coronal)	10.24	2.02	10.66	2.66	10.97	2.56	11.31	2.54	11.22	2.15	12.55	2.36
	hip (transverse)	13.52	3.07	14.91	3.36	13.55	3.67	14.62	3.05	17.47	4.98	15.55	2.94
	knee (sagittal)	62.06	4.62	60.52	4.53	66.79	5.53	66.64	4.46	63.36	5.71	65.59	6.48
	ankle (sagittal)	29.56	3.90	31.67	4.05	30.96	4.06	32.86	6.87	32.79	5.41	34.07	5.97
	ankle (coronal)	16.63	5.86	17.09	4.57	15.86	5.17	17.41	3.74	18.32	4.49	16.61	4.01
	ankle (transverse)	13.06	3.71	13.35	3.08	18.58	4.87	23.01	6.00	22.39	2.98	26.60	6.72
	functional leg length	1.00	0.00	0.94	0.08	0.92	0.06	1.00	0.00	0.95	0.09	0.96	0.10

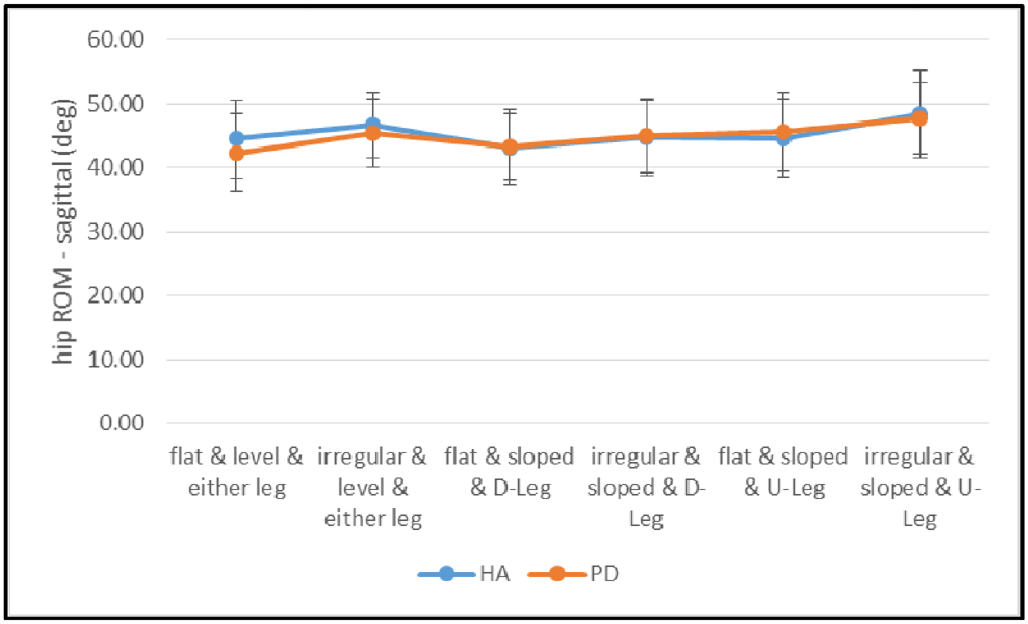


Figure 3.8. Mean Sagittal Hip ROM Per Condition.

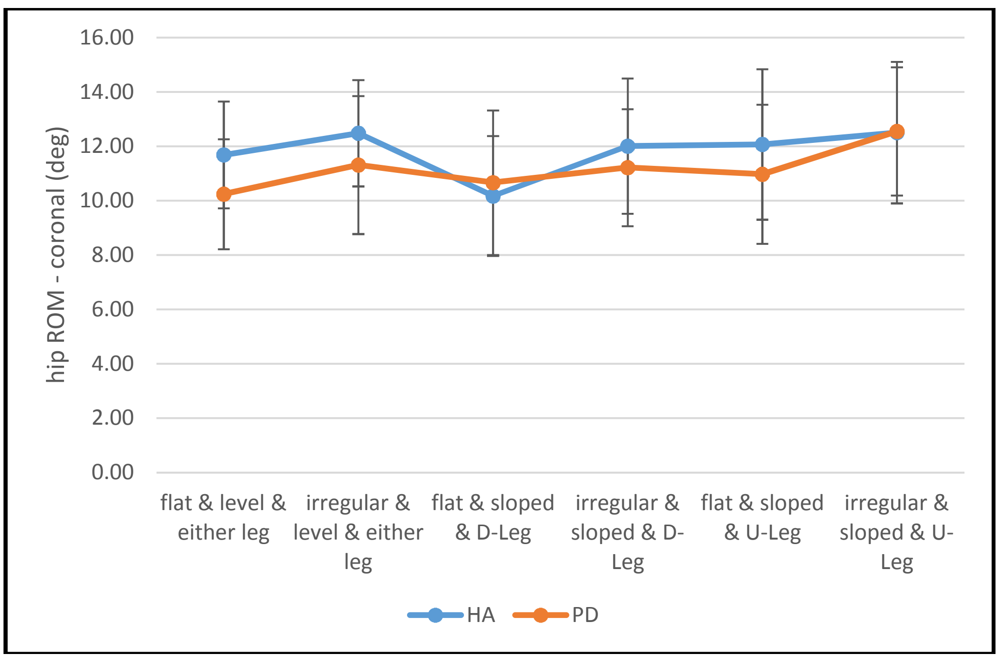


Figure 3.9. Mean Coronal Hip ROM Per Condition.

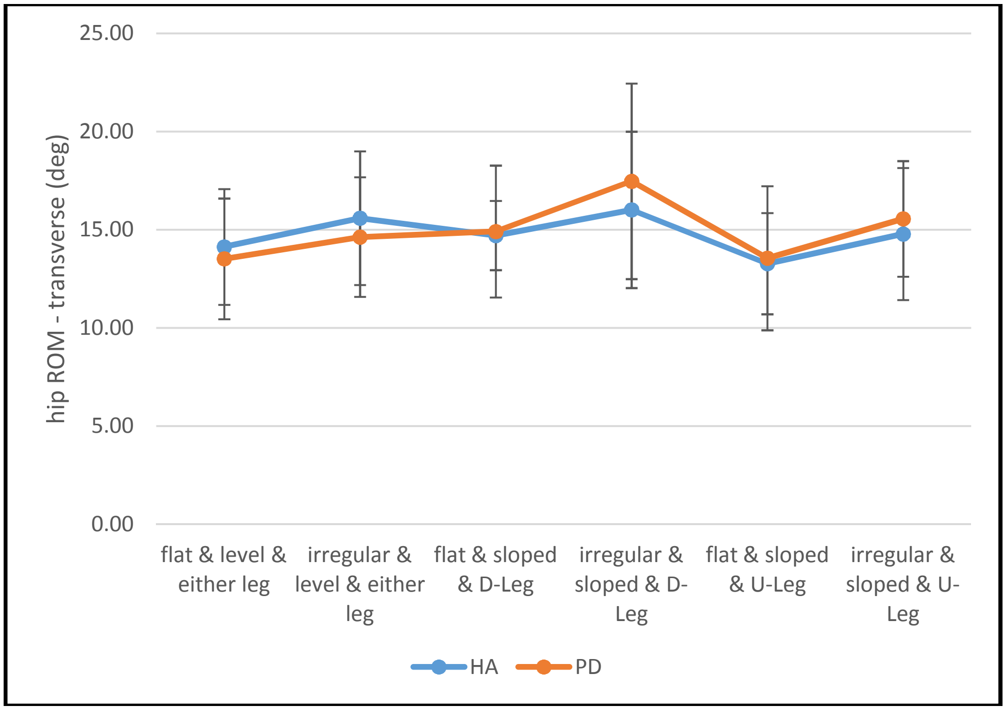


Figure 3.10. Mean Transverse Hip ROM Per Condition.

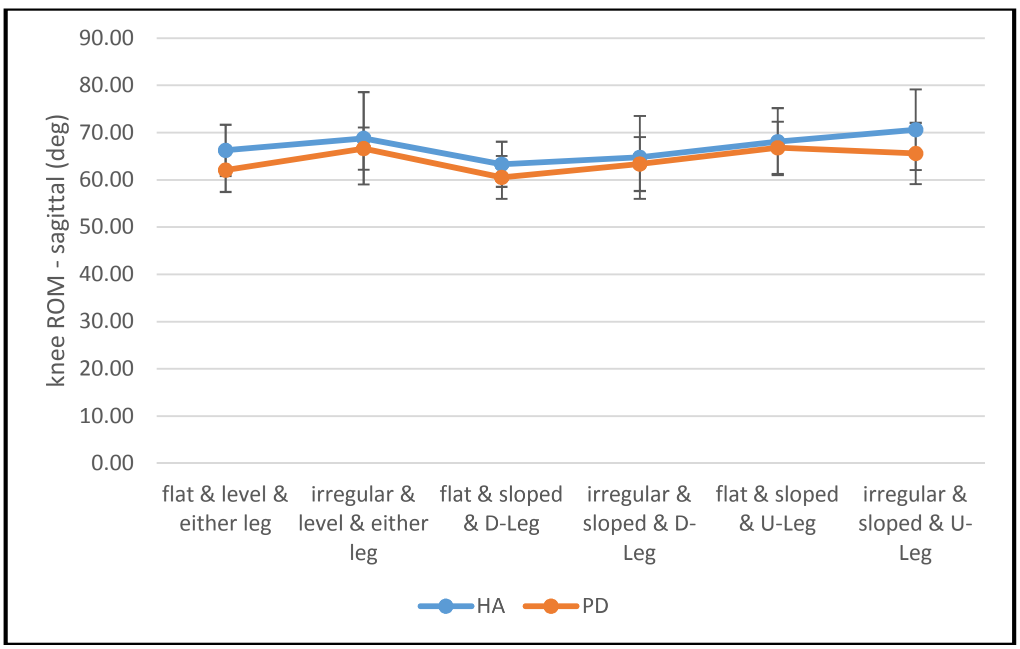


Figure 3.11. Mean Sagittal Knee ROM Per Condition.

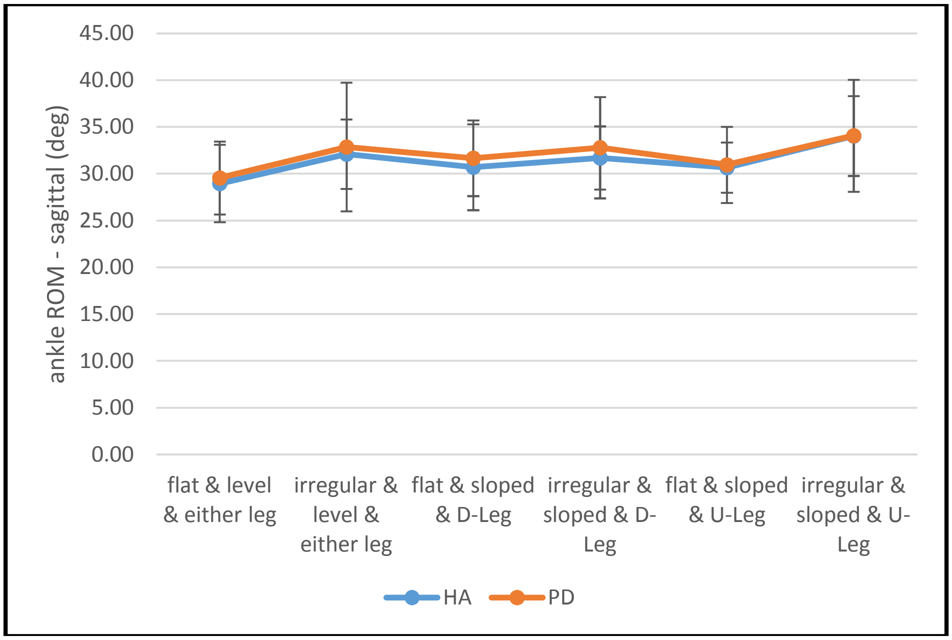


Figure 3.12. Mean Sagittal Ankle ROM Per Condition.

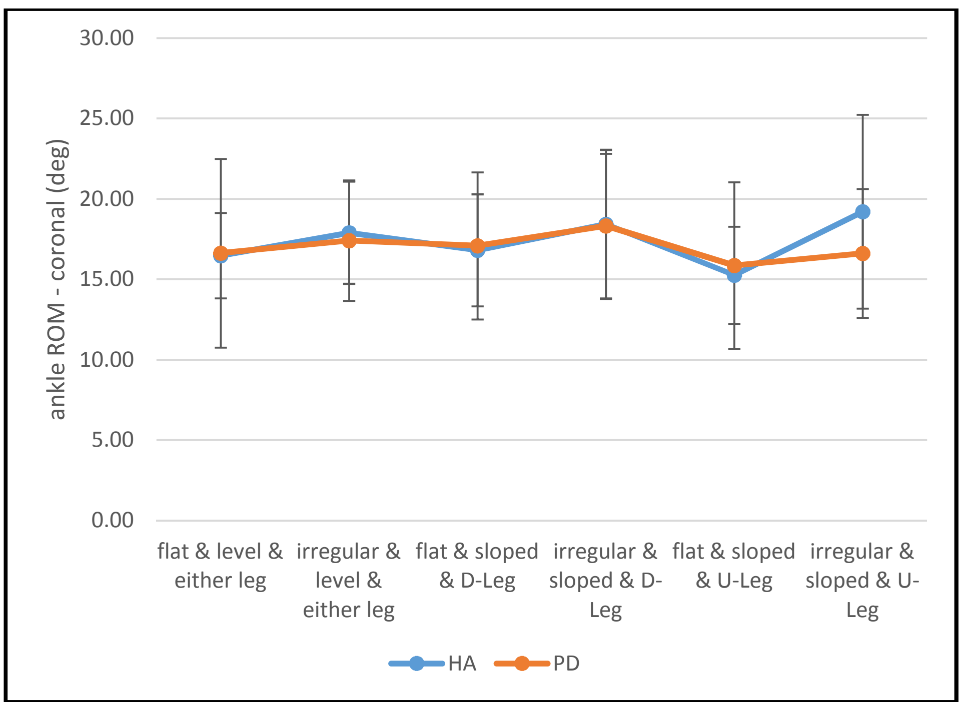


Figure 3.13. Mean Coronal Ankle ROM Per Condition.

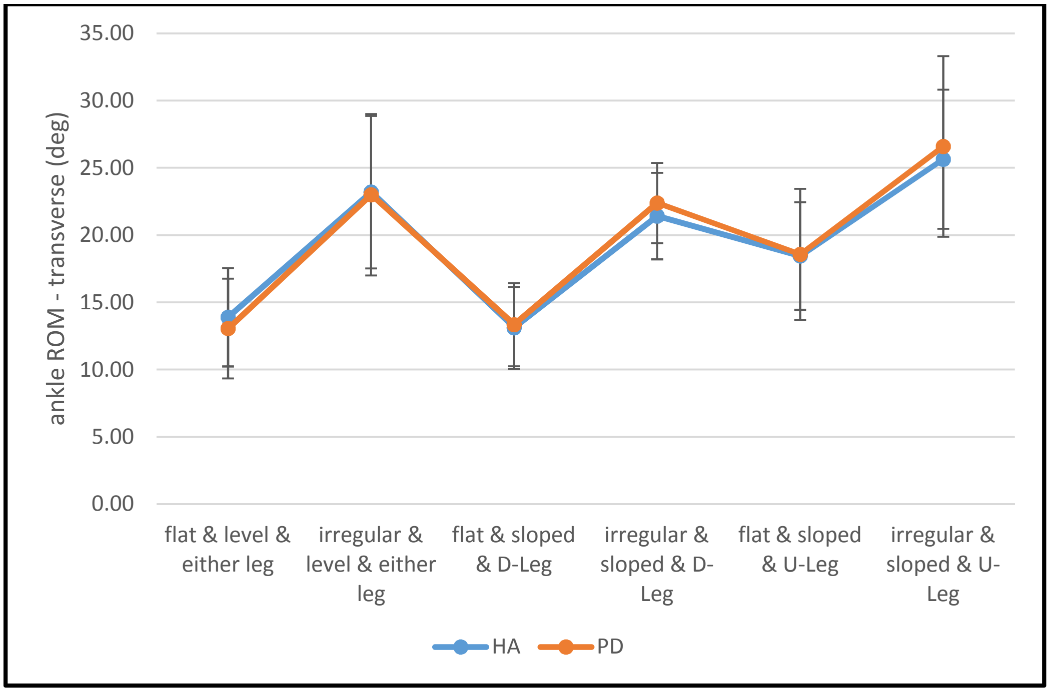


Figure 3.14. Mean Ankle ROM Per Condition.

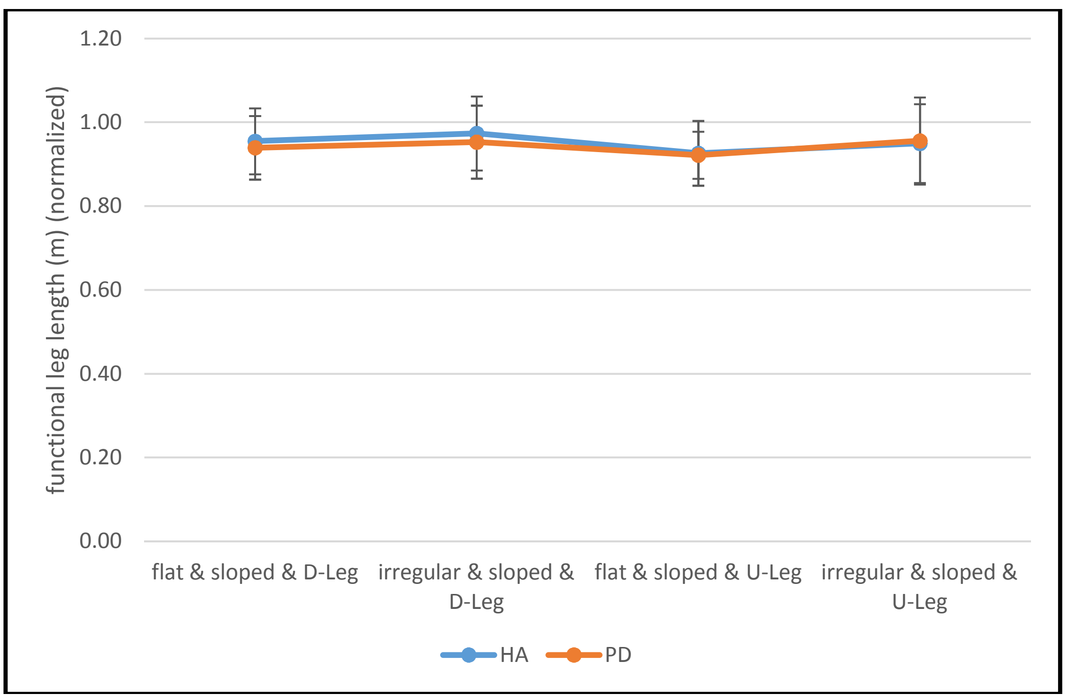


Figure 3.15. Mean Functional Leg Length Per Condition.

Table 3.3. Trunk/Stability Parameters – Descriptive Statistics.

		Surface Effects					
		ANOVA results		***Pairwise Comparison results (Flat to Irregular Terrain)***			
GROUP	**Parameter**	***P-values (Within Group Effect)***		***% diff: 0_deg***	***Sig. P-values***	***% diff: 10_deg***	***Sig. P-values***
HO	***trunk ROM (sagittal plane)***	0.033	*	25.39%	0.034	--	--
	trunk ROM (coronal plane)	0.03	*	--	--	26.43%	0.023
	trunk ROM (tranverse plane)	0.108		--	--	--	--
	AP trunk acc COM RMS	0.181		--	--	--	--
	ML trunk acc COM RMS	0.006	*	15.11%	0.042	19.26%	0.001
	vertical trunk acc COM RMS	0.003	*	10.02%	0.010	12.21%	0.008
PD	***trunk ROM (sagittal plane)***	0.001	*	37.28%	0.009	--	--
	trunk ROM (coronal plane)	0.001	*	--	--	18.81%	0.004
	trunk ROM (tranverse plane)	0.013	*	12.72%	0.034	15.76%	0.025
	AP trunk acc COM RMS	0.012	*	20.55%	0.028	30.40%	0.021
	ML trunk acc COM RMS	0.004	*	17.30%	0.025	27.20%	0.002
	vertical trunk acc COM RMS	0.049	*	8.75%	0.016	--	--

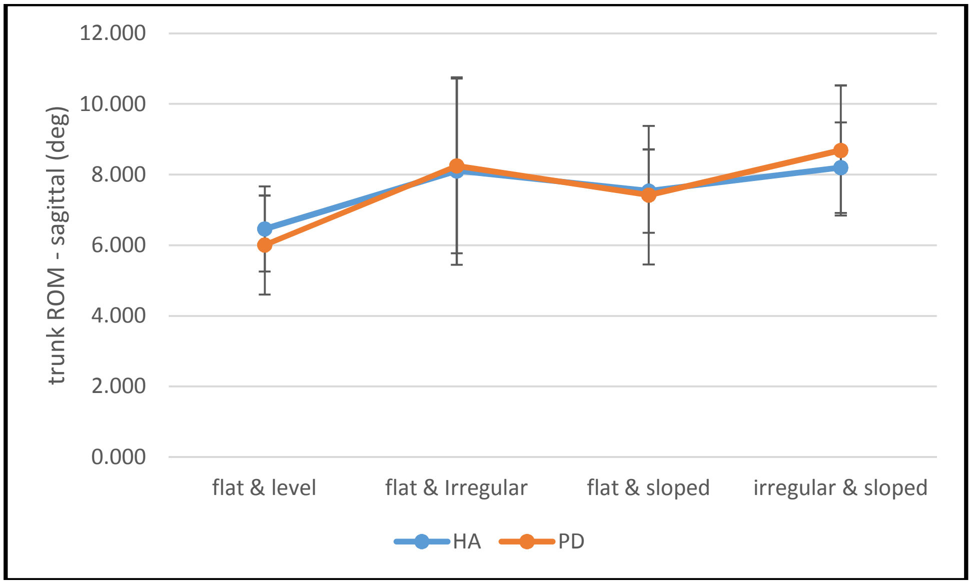


Figure 3.16. Mean Trunk Range of Motion – Sagittal Plane.

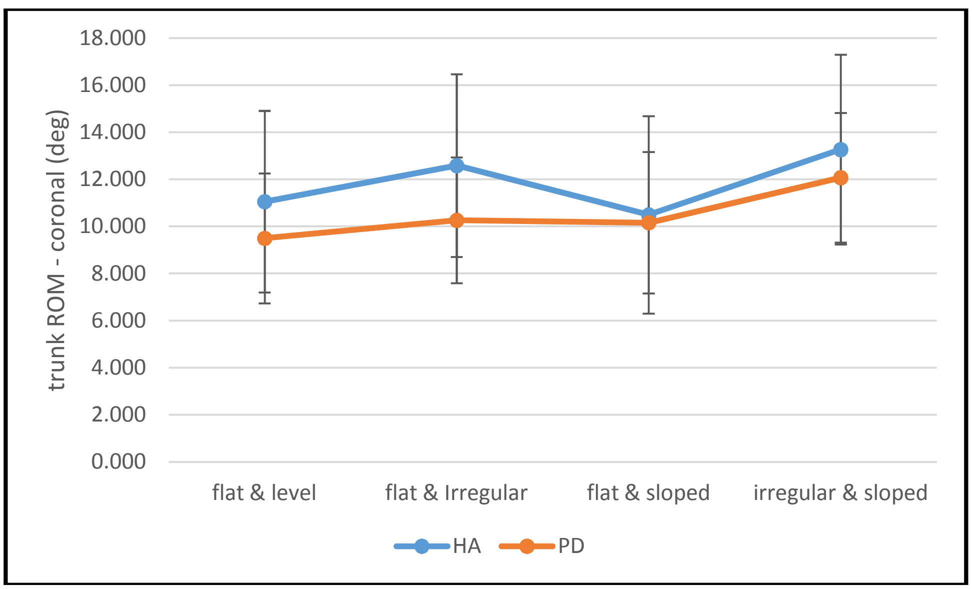


Figure 3.17. Mean Trunk Range of Motion – Coronal Plane.

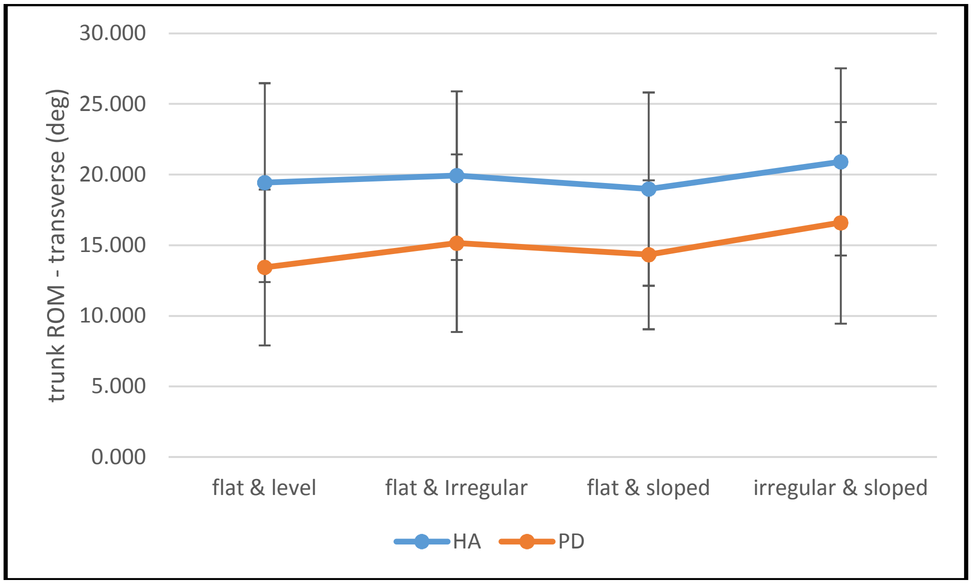


Figure 3.18. Mean Trunk Range of Motion – Transverse Plane.

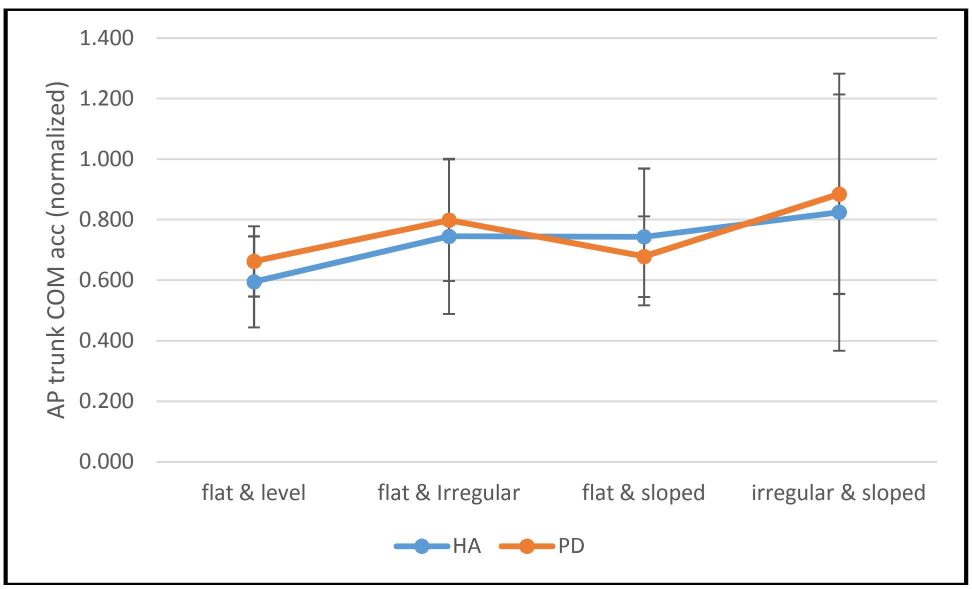


Figure 3.19. Anterior/Posterior Trunk COM Acc RMS.

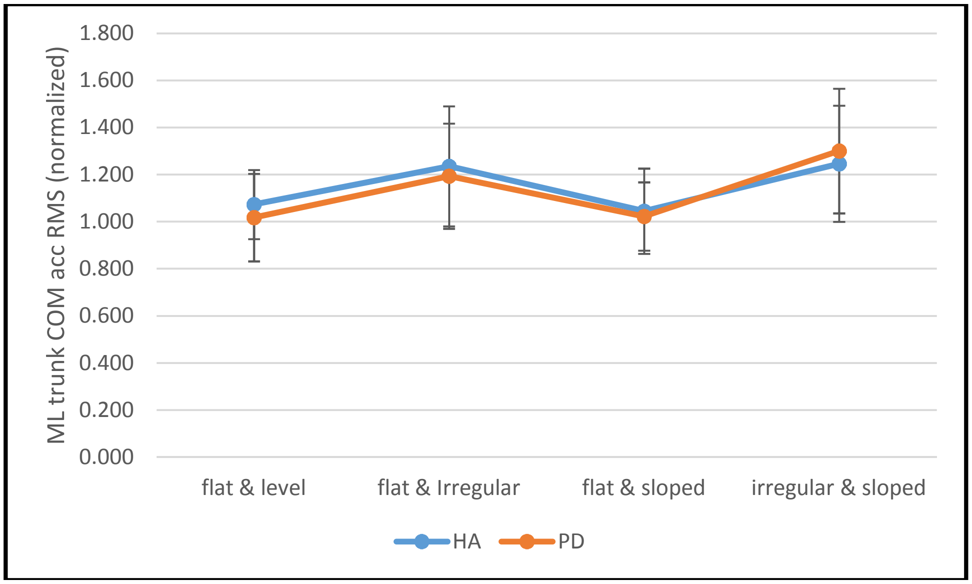


Figure 3.20. Mean Mediolateral Trunk COM Acc RMS.

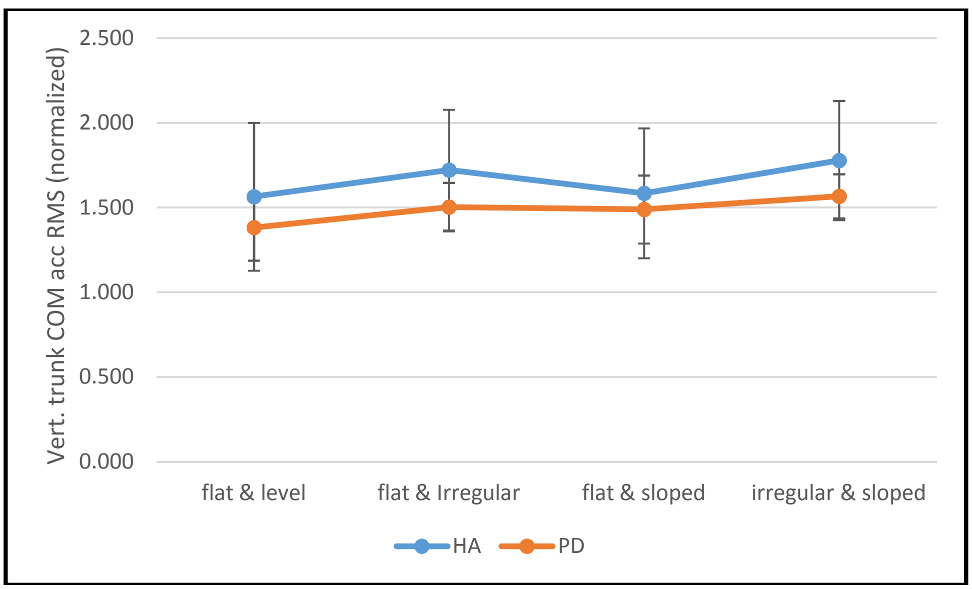


Figure 3.21. Mean Vertical Trunk COM Acc RMS.

trunk/stability parameters.

3.1.2 Overall Effects of Parkinson, Surface, and Slope

3.1.2.1 Spatiotemporal Parameters

The repeated measures MANOVA test performed on the spatial temporal 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: speed ($p<.001$), cadence ($p=.004$), step length ($p<.001$), double limb support time ($p=.014$), and single limb support time ($p=.014$).

3.1.2.2 Lower Limb 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 lower limb 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 ($p<.001$). Furthermore, repeated measures ANOVAs identified that 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).

3.1.2.3 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).

3.1.3 Analysis of Healthy Age-Matched Participants

3.1.3.1 Spatiotemporal Parameters

As indicated in Table 3.4, in the healthy age-matched group both speed (p=.003) and step length (p=.007) significantly changed due to the main effect of surface. At the pairwise comparison level the following significant changes were observed from the flat to the irregular surface:

- Speed:
    - on the level condition: decreased ↓
- step length:
    - on the level condition: decreased ↓

Table 3.4. Spatiotemporal Parameters – RM ANOVA and Pairwise Results Per Group.

		Surface Effects					
		ANOVA results		*Pairwise Comparison results (Flat to Irregular Terrain)*			
GROUP	**Parameter**	***P-values (Within Group Effect)***		***% diff: 0_deg***	***Sig. p-values***	***% diff: 10_deg***	***Sig. p-values***
HO	***Speed***	0.003	*	-10.48%	0.001	--	--
	cadence	0.138		--	--	--	--
	step w	0.076		--	--	--	--
	step l	0.007	*	-8.01%	0.002	--	--
	step wV	0.125		--	--	--	--
	single support time	0.078		--	--	--	--
	double support time	0.078		--	--	--	--
PD	***Speed***	0.003	*	-9.33%	0.015	-13.20%	0.004
	cadence	0.014	*	--	--	-7.54%	0.013
	step w	0.459		--	--	--	--
	step l	0.008	*	-6.18%	0.002	--	--
	step wV	0.271		--	--	--	--
	single support time	0.086		--	--	--	--
	double support time	0.086		--	--	--	--

3.1.3.2 Lower Limb Kinematic Parameters

3.1.3.2.1 Surface Effect

As indicated in Table 3.5, in the healthy age-matched group hip range of motion in sagittal (p=.001) and coronal (p=.024) planes, and ankle range of motion in the transverse plane (p<.001) significantly changed due to the main effect of surface. At the pairwise comparison level the following significant changes were observed from the flat to the irregular surface:

- hip range of motion in the sagittal plane:
    - in the down-slope lower limb on the cross-slope: increased ↑
    - in the up-slope lower limb on the cross-slope: increased ↑
- hip range of motion in the coronal plane:
    - in the down-slope lower limb on the cross-slope: increased ↑
- ankle range of motion in the transverse plane:
    - in either lower limb on the level condition: increased ↑
    - in the down-slope lower limb on the cross-slope: increased ↑
    - in the up-slope lower limb on the cross-slope: increased ↑

3.1.3.2.2 Limb Position Effect

As indicated in Table 3.6, in the healthy age-matched group hip range of motion in sagittal (p=.001), coronal (p=.001), and transverse (p=.014) planes; knee range of motion in the sagittal plane (p=.001); and ankle range of motion in the transverse plane (p=.006) significantly changed due to the main effect of the position of the lower limb of focus. Pairwise comparisons with significant changes from one limb to the next are given below. Note that because the kinematics did not change from one limb to the next in the

Table 3.5. Lower Limb Kinematic Parameters – ANOVA and Pairwise Comparison Results Per Group – Surface Effect.

		Surface Effects									
		ANOVA results		***Pairwise Comparison results (Flat to Irregular Terrain)***							
				0_deg Cross-slope				***10_deg Cross-slope***			
GROUP	***Parameter***	***P-values (Within Group Effect)***		***% diff: DS Leg***	***Sig. p-values***	***% diff: US Leg***	***Sig. p-values***	***% diff: DS Leg***	***Sig. p-values***	***% diff: US Leg***	***Sig. p-values***
HO	***hip (sagittal)***	0.001	*	--	--	--	--	3.59%	0.05	8.37%	0.00
	Hip (coronal)	0.024	*	--	--	--	--	18.05%	0.01	--	--
	hip (transverse)	0.059		--	--	--	--	--	--	--	--
	knee (sagittal)	0.132		--	--	--	--	--	--	--	--
	ankle (sagittal)	0.134		--	--	--	--	--	--	--	--
	ankle (coronal)	0.07		--	--	--	--	--	--	--	--
	ankle (transverse)	0	*	66.92%	0.00	66.92%	0.00	63.33%	0.00	38.92%	0.00
	functional leg length	0.149		--	--	--	--	--	--	--	--
PD	***hip (sagittal)***	0.001	*	7.14%	0.00	7.14%	0.00	--	--	4.84%	0.03
	hip (coronal)	0.019	*	10.47%	0.04	10.47%	0.04	--	--	14.38%	0.01
	hip (transverse)	0.057		--	--	--	--	--	--	--	--
	knee (sagittal)	0.009	*	7.37%	0.00	7.37%	0.00	--	--	--	--
	ankle (sagittal)	0.021	*	11.18%	0.03	11.18%	0.03	--	--	--	--
	ankle (coronal)	0.417		--	--	--	--	--	--	--	--
	ankle (transverse)	0	*	76.11%	0.00	76.11%	0.00	67.71%	0.00	43.19%	0.00
	functional leg length	0.275		--	--	--	--	--	--	--	--

Table 3.6. Lower Limb Kinematic Parameters – ANOVA and Pairwise Comparison Results Per Group – Limb Position Effect.

		Leg Position Effects						
		ANOVA results		***Pairwise Comparison results (Down-slope to Up-slope Leg)***				
				10_deg Cross-slope				
GROUP	***Parameter***	***P-values (Within Group Effect)***		***% diff: Flat Terrain***	***Sig. p-values***	***% diff: Irregular Terrain***	***Sig. p-values***
HO	***hip ROM (sagittal)***	0.001	*	--	--	8.20%	0.000
	hip ROM (coronal)	0.001	*	18.69%	0.002	--	--
	hip ROM (transverse)	0.014	*	-9.72%	0.014	--	--
	knee ROM (sagittal)	0.001	*	7.56%	0.004	9.03%	0.004
	ankle ROM (sagittal)	0.316		--	--	--	--
	ankle ROM (coronal)	0.738		--	--	--	--
	ankle ROM (transverse)	0.006	*	40.73%	0.020	19.69%	0.023
	functional leg length	0.107		--	--	--	--
PD	***hip ROM (sagittal)***	0.026	*	--	--	6.27%	0.012
	hip ROM (coronal)	0.048	*	--	--	11.89%	0.020
	hip ROM (transverse)	0.011	*	--	--	--	--
	knee ROM (sagittal)	0.002	*	10.35%	0.009	3.53%	0.032
	ankle ROM (sagittal)	0.671		--	--	--	--
	ankle ROM (coronal)	0.202		--	--	--	--
	ankle ROM (transverse)	0.026	*	39.12%	0.021	--	--
	functional leg length	0.609		--	--	--	--

level condition all of those comparisons noted are only from the cross-slope condition and refer to a lower limb to upper limb directional comparison:

- hip range of motion in the sagittal plane:
    - along the irregular surface: ↑
- hip range of motion in the coronal plane:
    - along the flat surface: increased ↑
- hip range of motion in the transverse plane:
    - along the flat surface: increased ↑
- knee range of motion in the sagittal plane:
    - along the flat surface: decreased ↓
    - along the irregular surface: increased ↑
- ankle range of motion in the transverse plane:
    - along the flat surface: decreased ↓
    - along the irregular surface: increased ↑

3.1.3.2.4 Slope*Limb Position Interaction

As indicated in Table 3.7, in the healthy age-matched group hip range of motion in sagittal (p=.001), coronal (p=.001), and transverse (p=.014) planes; knee range of motion in the sagittal plane (p=.001); and ankle range of motion in the transverse plane (p=.006) significantly changed due to the main effect of the position of the lower limb of focus. (Note that all of these p-values are the same as those computed for the parameters affected by the simple limb position main effect). Pairwise comparisons with significant changes from one limb to the next with concurrent changes in slope are summarized below:

Table 3.7. Lower Limb Kinematic Parameters – ANOVA and Pairwise Comparison Results Per Group – Slope*Limb Position Interaction.

		Slope*Leg Position Interaction									
		ANOVA results		***Pairwise Comparison results***							
				0_deg*Either leg to 10_deg*Down-slope leg				***0_deg*Either leg to 10_deg*Up-slope leg***			
GROUP	***Parameter***	***P-values (Within Group Effect)***		***% diff: Flat Terrain***	***Sig. p-values***	***% diff: Irregular Terrain***	***Sig. p-values***	***% diff: Flat Terrain***	***Sig. p-values***	***% diff: Irregular Terrain***	***Sig. p-values***
HO	***hip x (ROM)***	0.001	*	--	--	--	--	--	--	--	--
	hip y (ROM)	0.001	*	-12.97%	0.011	--	--	--	--	--	--
	hip z(ROM)	0.014	*	--	--	--	--	--	--	--	--
	knee x(ROM)	0.001	*	-4.45%	0.004	--	--	2.77%	0.023	--	--
	ankle x(ROM)	0.316		--	--	--	--	--	--	--	--
	ankle y(ROM)	0.738		--	--	--	--	--	--	--	--
	ankle z(ROM)	0.006	*	--	--	--	--	32.77%	0.002	--	--
	functional leg length	0.107		--	--	--	--	--	--	--	--
PD	***hip x (ROM)***	0.026	*	--	--	--	--	7.47%	0.029	5.17%	0.012
	hip y (ROM)	0.048	*	--	--	--	--	--	--	--	--
	hip z(ROM)	0.011	*	--	--	19.44%	0.015	--	--	--	--
	knee x(ROM)	0.002	*	--	--	-4.92%	0.007	7.62%	0.001	--	--
	ankle x(ROM)	0.671		--	--	--	--	--	--	--	--
	ankle y(ROM)	0.202		--	--	--	--	--	--	--	--
	ankle z(ROM)	0.026	*	--	--	--	--	42.18%	0.000	15.60%	0.004
	functional leg length	0.609		--	--	--	--	--	--	--	--

- hip range of motion in the coronal plane:
    - in either leg on the level condition to the down-slope leg on the cross-slope (with flat surface as a constant): decreased ↓
- knee range of motion in the sagittal plane:
    - in either leg on the level condition to the down-slope leg on the cross-slope (with flat surface as a constant): decrease ↓
    - In either leg on the level condition to the up-slope leg of the cross-slope (with irregular surface as a constant): increase ↑
- Ankle range of motion in the transverse plane:
    - in either leg on the level condition to the up-slope leg of the cross-slope condition (with irregular surface as a constant): increase ↑

3.1.3.3 Trunk/Stability Parameters

As indicated in Table 3.8, in the healthy age-matched group trunk range of motion in the sagittal (p=.033) and coronal (p=.03) planes as well as trunk COM acceleration RMS in anterior/posterior (p=.006) and vertical (p=.003) directions were changed significantly due to the main effect of surface. At the pairwise comparison level the following significant changes were observed from the flat to the irregular surface:

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

Table 3.8. Trunk/Stability Parameters – ANOVA and Pairwise Comparison Results Per Group.

		Surface Effects					
		ANOVA results		***Pairwise Comparison results (Flat to Irregular Terrain)***			
GROUP	***Parameter***	***P-values (Within Group Effect)***		***% diff: 0_deg***	***Sig. p-values***	***% diff: 10_deg***	***Sig. p-values***
HO	***trunk ROM (sagittal)***	0.033	*	25.39%	0.034	--	--
	trunk ROM (coronal)	0.03	*	--	--	26.43%	0.023
	trunk ROM (transverse)	0.108		--	--	--	--
	A/P trunk COM acc RMS	0.181		--	--	--	--
	M/L trunk COM acc RMS	0.006	*	15.11%	0.042	19.26%	0.001
	Vert. trunk COM acc RMS	0.003	*	10.02%	0.010	12.21%	0.008
PD	***trunk ROM (sagittal)***	0.001	*	37.28%	0.009	--	--
	trunk ROM (coronal)	0.001	*	--	--	18.81%	0.004
	trunk ROM (transverse)	0.013	*	12.72%	0.034	15.76%	0.025
	A/P trunk COM acc RMS	0.012	*	20.55%	0.028	30.40%	0.021
	M/L trunk COM acc RMS	0.004	*	17.30%	0.025	27.20%	0.002
	Vert. trunk COM acc RMS	0.049	*	8.75%	0.016	--	--

  - on the cross-slope: increased ↑
- trunk COM acceleration RMS in the vertical directions:
  - on the level condition: increased ↑
  - on the cross-slope: increased ↑

3.1.4 Analysis Of Participants With Parkinson

3.1.4.1 Spatiotemporal Parameters

In the group of persons with PD, speed, cadence, and step length were all significantly affected by the main effect of surface. At the pairwise comparison level the following significant changes were observed from the flat to the irregular surface:

- speed:
  - on the level condition: decreased ↓
  - on the cross-slope: decreased ↓
- cadence:
  - on the cross-slope: decreased ↓
- step length:
  - on the level condition: decreased ↓

3.1.4.2 Lower Limb Kinematic Parameters

3.1.4.2.1 Surface Effect

In the persons with PD group hip range of motion in sagittal ($p=.001$) and coronal ($p=.019$) planes, knee range of motion in the sagittal plane ($p=.009$), and ankle range of motion in the sagittal ($p=.021$) and transverse ($p<.001$) planes significantly changed due to the main effect of surface. At the pairwise comparison level the following significant changes were observed from the flat to the irregular surface:

- hip range of motion in the sagittal plane:
    - in either limb on the level condition: increased ↑
    - in the up-slope lower limb on the cross-slope: increased ↑
- hip range of motion in the coronal plane:
    - in either limb on the level condition: increased ↑
    - in the up-slope lower limb on the cross-slope: increased ↑
- knee range of motion in the sagittal plane:
    - in either limb on the level condition: increased ↑
- ankle range of motion in the sagittal plane:
    - in either limb on the level condition: increased ↑
- ankle range of motion in the transverse plane:
    - in either lower limb on the level condition: increased ↑
    - in the down-slope lower limb on the cross-slope: increased ↑
    - in the up-slope lower limb on the cross-slope: increased ↑

3.1.4.2.2 Limb Position Effect

In the persons with PD group hip range of motion in sagittal (p=.026), coronal (p=.048), and transverse (p=.011) planes; knee range of motion in the sagittal plane (p=.002); and ankle range of motion in the transverse plane (p=.026) significantly changed due to the main effect of the position of the lower limb of focus. Pairwise comparisons with significant changes from one limb to the next are given below. Note that because the kinematics did not change from one limb to the next in the level condition all of those comparisons noted are only from the cross-slope condition and refer to a lower limb to upper limb directional comparison:

- hip range of motion in the sagittal plane:
  - along the irregular surface: increased ↑
- hip range of motion in the coronal plane:
  - along the irregular surface: increased ↑
- knee range of motion in the sagittal plane:
  - along the flat surface: decreased ↓
  - along the irregular surface: increased ↑
- ankle range of motion in the transverse plane:
  - along the flat surface: decreased ↓

3.1.4.2.3 Slope*Limb Position Effect

In the persons with PD group hip range of motion in sagittal (p=.026), coronal (p=.048), and transverse (p=.011) planes; knee range of motion in the sagittal plane (p=.002); and ankle range of motion in the transverse plane (p=.026) significantly changed due to the main effect of the position of the lower limb of focus. (Note that all of these p-values are the same as those computed for the parameters affected by the simple limb position main effect. Pairwise comparisons with significant changes from one limb to the next with concurrent changes in slope are summarized below:

- hip range of motion in the sagittal plane:
  - in either leg on the level condition to the up-slope leg on the cross-slope (with flat surface as a constant): increased ↑
  - in either leg on the level condition to the up-slope leg on the cross-slope (with irregular surface as a constant): increased ↑

- hip range of motion in the transverse plane:
    - in either leg on the level condition to the down-slope leg on the cross-slope (with irregular surface as a constant): increased ↑
- knee range of motion in the sagittal plane:
    - in either leg on the level condition to the down-slope leg on the cross-slope (with irregular surface as a constant): decrease ↓
    - In either leg on the level condition to the up-slope leg of the cross-slope (with flat surface as a constant): increase ↑
- Ankle range of motion in the transverse plane:
    - in either leg on the level condition to the up-slope leg of the cross-slope condition (with flat surface as a constant): increase ↑
    - in either leg on the level condition to the up-slope leg of the cross-slope condition (with irregular surface as a constant): increase ↑

3.1.4.3 Trunk/Stability Parameters

In the group of persons with PD all of the trunk/stability parameters were significantly affected by the surface effect: trunk range of motion in the sagittal (p=.001), trunk range of motion in the coronal plane (p=.001), trunk range of motion in the transverse plane (p=.013), trunk COM acceleration RMS in Medial/Lateral directions (p=.001), trunk COM acceleration RMS in the anterior/posterior directions (p=.001), and trunk COM acceleration RMS in the vertical directions (p=.049). At the pairwise comparison level the following significant changes were observed from the flat to the irregular surface:

- trunk range of motion in the sagittal plane:

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

3.1.5 Effect Of Parkinson

As the MANOVA did not reveal an overall main effect of PD on the difference of the gait parameters between groups, such a main effect is not the focus of this paper. However, it should be noted that univariate tests revealed that those parameters which were most significantly affected per condition were not always the same per group. This suggests that each group was affected differently by the test conditions or that they chose alternative approaches to tackling the different conditions.

3.1.6 Posttrial Questionnaire

The posttrial questionnaire contained a rich source of information, and the responses that were of particular interest in terms of this thesis are given below. Table 3.9 reveals that overall the participants had an eventful fall history, making them primary candidates in assessing terrains that are to be used in challenging the gait of patients in the Treadport rehabilitation environment. (An eventful fall history even within a population as small as this also gives testament to the severity of the problem of falls among those with PD). As indicated in Table 3.10, both groups did not perceive any of the experimental surface/slope setups to be particularly difficult to navigate. However, the responses do reveal that there was a degree of difference of perceived difficulty between each surface and that overall the irregular surface on a cross-slope condition was the most challenging. Despite not having perceived a great deal of challenge on the surfaces, Table 3.11 reveals that the participants did recognize the importance of examining gait on such surfaces because of the presence of similar terrain in the real world.

3.2 Discussion

3.2.1 Main Effects

3.2.1.1 Surface Versus Cross-Slope

From the main effects identified through the MANOVA, it appears that irregular surface (as defined in our study) had more of an effect than surface on the gait of both the healthy age-matched group as well as the group of participants with PD, as surface had a significant main effect on all of the groups of parameters of focus in this study. Furthermore, it is interesting to note the lack of significance of the surface*slope interaction. This absence of an interaction seems to indicate that adding irregularity on

Table 3.9. Fall History of Participants with PD in Past 6 Months.

	PD	
	Mean	***StdDev***
# of Falls	2.67	0.93
# of Near Falls	3.75	1.21

Table 3.10. Perceived Difficulty in Maintaining Stability Per Experimental Terrain.

Surface/Slope Condition	***HO***		***PD***	
	Mean	***StdDev***	***Mean***	***StdDev***
Even Surface, 0 deg	1.11	0.33	1.22	0.44
Irregular Surface, 0 deg	1.44	0.53	2.11	0.78
Even Surface, 10 deg	1.56	0.73	1.67	0.71
Irregular Surface, 10 deg	1.67	0.87	2.33	1.00

Note: Scores are based on a 1 to 5 Likhert scale with 1 indicated ‘not difficult at all’ and 5 corresponding to ‘very difficult.

Table 3.11. Response to ‘Have You Encountered Similar Terrain Before?’.

	HO	***PD***
No	0	0
Yes	9	9
If Yes, Where?	mountains, hiking, Antarctica, cobblestone streets, city walking, driveways, rock gardens, curbs, hunting, fishing, walking in the yard, trail running, stream beds	

top of a cross-slope surface (or vice versa) does not seem to exacerbate the degree of challenge/gait modifications that is involved in traversing such a surface.

3.2.1.2 Effect of Parkinson

Although a group effect was not identified through the MANOVA, other studies indicate differences in the effect of challenging conditions on those with PD versus those who are healthy and age matched. [51] The lack of the identification of a group effect in the case of this study might be best explained by the fact that most of the participants with PD who were recruited were recruited from a rehab facility. They were thus quite healthy due to their regular exercise regimes and therefore might not be as good a representation of the general population with PD meeting the criteria set forth in this study. Two participants exhibited more advanced signs of PD in terms of the effect on gait, even though all of the participants met the same criteria, though their influence on the overall statistics in the end was not significant. It is recommended that additional studies be conducted in the future with similar challenging terrain and larger groups of PD who have met more stringent criteria in order to avoid less diversity in the groups so that more definitive conclusions might be drawn.

3.2.2 Analysis Of Healthy Age-Matched Participants

3.2.2.1 Spatiotemporal Parameters

Overall the healthy age-matched participants walked more slowly and with shorter steps when walking on the irregular terrain in comparison to the control flat terrain, suggesting a trend towards trying to maintain a certain 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 as opposed to a cross-slope. Irregular and uneven terrain studies with healthy age-matched persons on level ground in the past have revealed similar strategies of adopting more conservative step patterns as a means of coping with the true added stability challenges or cautiously anticipated/perceived additional challenge presented by such surfaces. Such conservatism has been described as being an overall means of more easily managing trunk stability and reducing head acceleration so as to improve visual input because both of these measures are important in terms of overall stability maintenance.[21,29]

It is interesting to note that step width variability was not significantly affected, because it has been shown to be significantly affected both in healthy age-matched and healthy young participants on irregular terrain in the past.[29] Step variability in general has been shown to be more energetically taxing because it involves less passive movement and thus is an indicator of more active balance control.[25,47] Perhaps other step variability parameters (such as in regards to step length, which was significantly affected as a mean) might have revealed more concerning, more active postural control/challenge as elicited by the terrain. However, the fact that step width variability in particular was not affected indicates that the irregular terrain was not particularly challenging to navigate because increased step width variability has been linked to fall risk in older adults given the difficulty that they especially have in maintaining mediolateral stability. The specific irregular terrains used in the past studies noted for their step width variability have included random, smaller, more greatly separated and/or less exposed irregularities (e.g., they have included obstructions placed beneath surfaces). However, the irregularities used in this study consisted of well-lit irregularities with distinguishable colors and shapes and with gaps small enough between them that they were not as much of a tripping hazard as larger gaps might be.[29] These combined characteristics overall might have made establishing a more consistent pattern of walking over the irregular terrain in this study an easier task than in those others afore-described. Stone pathways in general were identified as being a particularly challenging surface on which to maintain one's balance as revealed in the preliminary questionnaire, which precipitated the selection of this terrain for this study. The results of the step parameters at least seem to indicate that the terrain selected for this study was not exactly what the questionnaire participants were referring to or that cobblestones in general might not be as particularly challenging in navigating without the addition of added environmental challenges (poor lighting, etc.). It should also be taken from this study that in future irregular terrain studies in general, the degree of difficulty of the setup of the irregularities should be well assessed first before proceeding to use it to examine its effects.

3.2.2.2 Lower Limb Kinematics Parameters

3.2.2.2.1 Surface Effect

Overall across the level condition, surface only significantly affected ankle range of motion in the transverse plane. No significant changes were observed in any of the kinematics in the sagittal or coronal planes. This suggests that no significant attempts were made to increase vertical clearance between the foot and the surface irregularities in order to avoid tripping, but that instead they may have used a different strategy to avoid tripping. The height of the tallest protuberating 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 would have been unnecessary if the areas of greatest difference in height (i.e., the spaces between the stones) were avoided. Such avoidance maneuvering might explain the increase of the range of motion of the ankle in the transverse direction, because the directions of the longest axis of each stone's face varied and thus in order to achieve avoiding the spaces between each stone, one would need to point his/her toes in various directions from step to step. Surface irregularities above 1.5 cm are shown to increase risk of ankle sprain and thus if such a strategy were taken it would have meant that the participants were reducing their likelihood of ankle injury in addition to preventing trips. [52] Past studies of irregular terrain have not included a focus on internal/external rotation motion of the ankle. Most, in fact, have chosen to veer from focusing on lower limb kinematics in general because of the variability in step patterns that a variable surface elicits and the stability implications suggested by such step variability. One study with healthy young adults that strove to look more at the energetics of walking on irregular terrain, however, did focus on some lower limb kinematics; therefore it is this study whose results may be compared to the kinematic results reflected in the present study.[47] In that study little change was observed in terms of lower limb ankle ranges, which is similar to what was seen in the case of the present study in terms of the level irregular condition effects. The same study also found that while the angles did not change significantly, their variability did as well as the moments on the knee and hip, which might have thus also been revealed in the case of the present study had such parameters been measured.

In terms of the effect of surface across the cross-slope condition, hip range of motion in the sagittal and coronal plane and ankle range of motion in the transverse plane of the down-slope leg were significantly increased. In the case of the up-slope leg, however, only the hip range of motion in the sagittal plane and ankle range of motion in the transverse plane were affected significantly. The significant ankle range of motion changes might be best explained by the theory of stone stepping strategy mentioned in the spatiotemporal results section for this group. However, this increased range of motion on the combination of irregularity as well as cross-slope might also be a result of the fact that cross-slopes in general elicit significant changes in ankle motion in the transverse plane and therefore the irregularity might have just exacerbated this cross-slope effect.[36] The same study hypothesized that greater internal rotation in the up-slope ankle on cross-slopes might be due to an attempt to help with push off and that the more neutral positioning of the down-slope ankle on cross-slopes might be an attempt to control the down-slope deviation of the COM; these explanations may be applicable to a cross-slope irregular condition as well. The fact that the hip was only affected by changes in surfaces on the cross-slope but not the level condition indicates a possible surface*slope interaction effect on these kinematic parameters specifically. Different increases in hip ranges of motion indicates that the surfaces across the cross-slope resulted in asymmetric compensation strategies between limbs. Asymmetry in general has been reflected in cross-slope studies without irregular surfaces in the past, and 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 in general. In particular, pelvic obliquity has been identified as the main means through which the functional leg length discrepancies are achieved, most especially in the mediolateral directions because of the danger of falling and slippage in such directions on a cross-slope.[32] As significant changes across the surfaces on the cross camber slope involved the hip and were most asymmetric in the mediolateral directions (because the up-slope leg was not even significantly affected by the addition of irregularity, unlike the down-slope leg (p=.005)), this suggests that the irregular surface mimicked/compounded the effects of mediolateral instability presented by cross-slopes alone; further suggesting a surface*slope interaction in this case.

In the case of both legs on either the level and cross-slope conditions, ankle range of motion in the transverse plane was always increased by the addition of irregularity to the surface on which the participants tread. This surface effect trend further supports the fact that a stone stepping strategy might have existed as aforementioned. As no previous studies with irregular terrain have focused on ankle motion in this plane before, it may not be concluded that such a strategy is unique to the irregular terrain chosen (and thus is a 'stone' stepping strategy rather than a simple strategy to navigating all types of irregularities including stones).

3.2.2.2.2 Limb Position Effect

Limb position was only included as an additional repeated measure in the case of the statistics performed on the kinematics groups, in anticipation of the significant asymmetry between lower limb kinematics on cross-slopes in particular as identified by other cross-slope studies.[32] No asymmetry was seen in the case of the level condition because values between limbs were simply averaged for such trials. Lower limb position in the case of the cross-slope, flat surface condition significantly affected hip range of motion in the coronal and transverse planes (i.e., increased by 18.7% (p=.002) and decreased by 9.7% (p=.014)), knee range of motion in the sagittal plane (i.e., increased by 7.6% (p=.004)), and ankle range of motion in the transverse plane (i.e., increased by

40.7%). While in the case of lower limb position on the cross-slope, irregular surface condition, only the following parameters were affected: hip range of motion in the sagittal plane (increased by 8.2% ($p<.001$)), knee range of motion in the sagittal plane (increased by 9.0% ($p=.004$), and ankle range of motion in the transverse plane (increased by 19.7% ($p=.023$)). These results indicate that the main differences between limbs in the case of the irregular terrain and a cross-slope involved sagittal plane kinematics, suggesting that less concentration was made in using asymmetry to prevent slippage and falling in the mediolateral/coronal plane than was observed on the flat cross-slope condition.

3.2.2.2.3 Slope*Limb Position Interaction

As the position of the limb only affected differences in kinematics on the cross-slope condition, it is not surprising that a statistically significant slope*limb interaction was identified. Looking at the difference per limb going from level to cross-slope conditions, neither leg was significantly affected when the transitioning surface also included irregular terrain. This suggests that the addition of the irregular terrain made the ranges of motion of either leg on the cross-slope mimic those of either leg on a level condition with the same surface type. Transitioning from the level to cross-slope condition without the factor of an irregular surface, resulted in less motion by the hip in the coronal plane (i.e., decreased by 13% ($p=.011$)) and by the knee in the sagittal plane (i.e., decreased by 4.4% ($p=.004$)) in the down-slope leg. This suggests that they were the primary means through which an elongated functional leg length was consistently achieved during a trial. The same transition led to more motion by the knee in the sagittal plane (i.e., increased by 2.8% ($p=.023$)) and more motion by the ankle in the transverse plane (i.e., increased by

32.8% (p =.002)). This suggests that the knee was the primary means through which to achieve the extra toe clearance during the stance phase necessary when dealing with cross-slopes.

3.2.2.3 Trunk/Stability Parameters

Adjustments in the other parameters suggest individual components in stability management, but overall success in achieving stability through this management system was evaluated through the trunk movement. Past studies with irregular terrain on level ground have reported a decrease in trunk variability, however, only increases were detected in all of the trunk parameters when they were significantly affected in the case of either group.[25]

Overall, surface effect across the level condition resulted in a significantly impacted trunk range of motion in the sagittal plane and trunk COM acceleration RMS in the mediolateral and vertical directions. Greater trunk angle standard deviation results in the decreased likelihood of being able to recover from perturbations and thus are linked to an increase in fall risk; therefore an increase in general trunk range of motion might indicate similar risks. An increase in the step parameters in the same plane of the increased motion would be a concurrent biomechanical modification that might be made in order to alleviate the increased fall risk because it would increase the base of support boundaries so that the increased range of motion of the COM would be less likely to surpass them and result in a fall.[25] Because greater motion was observed in the sagittal plane without an increase in step length, this suggests that surface overall increased the instability of the healthy age-matched participants in the sagittal plane. Trunk variability has been tied to balance control, and thus simple increase in the variability in the movement in the mediolateral direction suggests that a greater amount of active control was necessary in the mediolateral directions with the added surface irregularity. The mediolateral directions are those in which older adults are most unstable and therefore the added control necessitated as a result of the irregular surfaces seemed to pose a greater fall risk for the healthy age-matched adults.

The overall surface effect on the cross-slope, significantly affected the trunk range of motion in the coronal plane as well as trunk COM RMS in the mediolateral and vertical directions. An increase in variability as well as an increase in range of motion suggests a greater fall risk in the coronal plane than was seen on the level terrain when irregularity was added (in which case only an increase in variability was observed) because the combined effect of these two significant changes would seem to indicate that more control was necessary in the mediolateral directions on such terrain in addition to more ability to recover from more extreme leaning states.

A past study involving irregular terrain on level ground, revealed significant surface effects for trunk RMS in all directions in both healthy and older participants.[25] Although significance was not observed in the case of the comparisons of the RMS in every direction from surface to surface in this study, it should be noted that a general trend of increasing RMS with added irregularity was consistent for every direction for both groups as it was for the other study. This was true even in the case of the comparison between the surfaces on a cross-camber condition. This suggests that the surface effect directly affected stability in all directions (despite the lack of significance effect on step variability) because trunk COM acceleration RMS was a direct measure of stability in this study.

3.2.3 Analysis Of Participants With Parkinson

3.2.3.1 Spatiotemporal Parameters

When walking on a level path, added irregularity resulted in a decrease in speed and step length, as it did with the healthy age-matched group. These adaptations in response to the surface therefore have the same general implications as those aforementioned in the healthy age-matched group spatiotemporal write-up. Although the same parameters were significantly affected in the case of both groups in the same condition, the participants with PD were less affected in that their speed and step lengths reduced by a lesser percentage than did those of the healthy age-matched group when introduced to the irregular terrain. Though these differences were not identified as being significant at the MANOVA level for the spatiotemporal parameters with a group or group*surface interaction, it hints at the fact that those with PD were walking more conservatively to being with and thus had to make less adjustments to comply with the changing surface.

In terms of surface effect when combined over a cross-slope, the irregular surface significantly affected change in spatiotemporal parameters for the group of participants with PD even though it did not affect any in the case of the group of healthy age-matched participants. This suggests that slope in combination with surface irregularity may have affected the group with PD more so than the healthy age-matched group even though an overall significant group*surface*slope interaction was not detected via the repeated measures MANOVA. Overall, when comparing a cross-slope with a regular/flat surface and an irregular surface, the irregular surface resulted in a significant decrease in the speed and cadence of the group with PD. This suggests a means of trying to develop a significantly greater conservative stepping pattern, which in turn suggests that the added degree of difficulty between the slope and irregular surface slope was significant. Looking at step and cadence alone, in fact, they were both smallest (in comparison to all of the surface/slope combinations) on the irregular surface/cross-slope combination surface, suggesting that it might have been the most challenging to navigate or may have been assumed as such despite the true challenges that it presented to the participants overall stability. As one final note, it is surprising that among the parameters most affected with the addition of the irregularity to the tilt, none of them include any of the mediolateral parameters considering the challenge to mediolateral stability that a cross-slope alone poses.

3.2.3.2 Lower Limb Kinematics Parameters

3.2.3.2.1 Surface Effect

Overall, across the level condition in the down-slope leg, surface significantly affected hip range of motion in the sagittal and coronal planes, knee range of motion in the sagittal plane, and ankle range of motion in the sagittal and transverse planes. As surface only affected ankle range of motion in the transverse plane in the case of the healthy age-matched group, this seems to indicate that the lower limb kinematics of those with PD were much more affected by the addition of the irregular terrain than they were in the case of the healthy age-matched group. The greater increase in motion in the sagittal plane across all joints is suggestive of a significant attempt to increase step clearance when surface irregularity was introduced. In addition, the increase in coronal plane motion by the hip is suggestive of potential increase in fall risk due to the mediolateral stability threats of cross-slopes.

The effects of surface on the down-slope leg on the cross-slope were similar to those effects on either leg of the healthy age-matched individuals when on a level condition (i.e., only the ankle range of motion of either of their legs was significantly different). In terms of the surfaces effect on the up-slope leg, on the other hand, the results followed a trend similar to that seen in the down-slope leg of the healthy age-matched participants (i.e., hip sagittal and coronal plane ranges of motion increased as did ankle range of motion in the transverse plane).

3.2.3.2.2 Limb Position Effect

The difference between the up-slope and down-slope limbs on a flat cross-slope was a greater degree of knee range of motion in the sagittal plane and ankle range of motion in the transverse plane in the up-slope leg. Greater knee range of motion in particular is to be expected because the up-slope leg must be more crouched in order to assume a foreshortened functional leg length. In terms of the difference between the two limbs on an irregular cross-slope, on the other hand, it was greater hip range of motion in the sagittal and transverse planes in the up-slope leg. This suggests that the hip may be more active altogether when irregular terrain is factored into a cross-slope. In particular it is interesting to note that there is a difference in hip rather than ankle transverse range of motion, as was the case with the flat cross-slope. This suggests that toes may be pointed in a similar direction on a flat or irregular cross-slope, but that such movement might be achieved more so by higher level joint kinematics (i.e., via hip rotation rather than a combination of joint movements necessary for internal/external ankle rotation) in the case of the irregular slope case.

3.2.3.2.3 Slope*Limb Position Interaction

Transitioning from a level to cross-slope condition, the kinematics of the down-slope leg were not significantly affected unless an irregular surface were present. With an irregular surface, the down-slope knee range of motion in the sagittal plane decreased during the slope transition. This indicates that irregularity might have resulted in the formation of a stiffer, more elongated down-slope leg. In terms of the up-slope leg, changes were seen with or without the factor of an irregular surface. Transitioning from a level to cross-slope condition with a constant irregular surface, the up-slope leg increased in hip movement in the sagittal plane and in ankle range of motion in the transverse plane. Without an irregular surface, similar hip and ankle changes were seen in addition to an increase in knee range of motion in the sagittal plane. This suggests that irregular surface on a cross-slope resulted in an overall longer up-slope functional leg length.

3.2.3.3 Trunk/Stability Parameters

On the level condition, surface specifically significantly increased trunk range of motion in the sagittal and transverse planes, and increased trunk COM acceleration RMS in every direction. On the cross-slope, however, surface effect significantly increased trunk range of motion in the coronal plane and transverse planes, and trunk COM acceleration RMS in the anteroposterior and mediolateral directions. As with the healthy age-matched groups, trunk range of motion in the sagittal plane was thus more affected in the case of irregular surface on a level condition, while trunk range of motion in the coronal plane was more affected in the case of irregular terrain in the case of a cross-slope. Greater motion in the sagittal plane during gait on level irregularities might have been a strategy to maintain stability or an indication of increased instability. As step length decreased concurrently with an increase in trunk motion in the sagittal plane for both groups, this created a greater risk of the COM projection crossing the base of support boundaries. Thus, suggesting that the trunk movement was more of a sign of fall risk rather than a successful answer in adapting to reduce such risk. Greater motion in terms of the coronal plane on irregularities on cross-slopes might similarly be viewed as either a stabilizing strategy and/or an indication of increased fall risk. No previous studies on cross-slope surfaces have focused on trunk/upper body movement, but a past study has suggested that trunk roll might be a strategy to draw the upper body closer to the vertical when pelvic obliquity is not apparent.[32]

It is interesting to note that trunk COM acceleration RMS in the anteroposterior directions seemed to have been most affected (in terms of percentage change) by the addition of irregularities to the surface on which subjects walked. This indicates that mediolateral stability was not the direction in which the main stability issues existed (as was also suggested by the lack of significant step parameter changes in the coronal plane already noted), despite the general mediolateral stability issues associated with aged populations.

Furthermore, it should be noted that unlike the healthy age-matched participants, surface affected every trunk kinematic and stability parameter significantly on one slope condition or the other. More variability overall in the trunk as well as greater range of motion in the same segment suggests that more challenge in maintaining stability was experienced by the participants with PD in comparison to the healthy age-matched adults when asked to walk on irregular terrain in general. Vertical trunk motion in particular was more affected in the case of the group with PD because it exhibited significant change in the case of surface effect on both slope conditions, while it was not significantly affected on either condition for the healthy age-matched group. The explanation for this increase in vertical movement might be that those with PD increased clearance between their feet and the potential trip hazards posed by the irregular surface more so than did the healthy age-matched participants. As this may have been a strategy to decrease fall risk, it could have potentially led to an increase in risk instead. The inability to prevent increased vertical movement in the trunk means greater movement in the head. Greater head movement in general poses an added challenge to stability in all directions because it can affect one's visual input and unimpaired visual input is key to successful obstacle crossing (and thus assumedly for successful navigation along irregular surfaces as well).[29]

CHAPTER 4

CONCLUSION

4.1 Discussion Summary

It is important to research challenging environments as well as the combined effect of various challenging conditions with respect to gait in order to better understand real world biomechanics because real world environments rarely involve simply level surfaces or surfaces with only a single type of element that poses a challenge to the stability of those who navigate across them. Hiking for instance (which is an especially popular activity in the state of Utah, where this study was conducted) presents a myriad of types of stability challenges that may only be overcome through multiple gait adaptations. It is especially important to focus on identifying the challenges that such real world conditions pose to those who are affected most significantly by them. Increasing age alone contributes to greater fall risk. With the overall aging of the world's population this means that a majority of the population should be the focus of such studies.

As hypothesized, the gait of those with PD and the healthy age-matched participants were both affected by surface irregularity in general because the separate MANOVAs of each group of parameters revealed an overall significant surface effect. On the other hand, no significant group effect was detected via the MANOVAs to support the additional hypothesis that there would be differences between the effects that surface and slope would have on each group. Despite this lack of an overall group*surface interaction, the trend of parameters that were most affected by surface per slant condition was not the same between the groups. This suggests that the groups, were in fact affected differently by surface irregularity. Similarly, no main slope effects were detected either, but the identification of a significant leg*slope interaction in the case of the group of kinematic parameters suggests that slope played a part in at least significantly affecting a change in kinematic differences between one leg and the other.

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). In addition, the fact that it focused on the combination of irregular terrain and cross-slopes with any population is unique as well, as such conditions have only been studied separately in the past. Furthermore, cross-slope studies in general have only involved healthy younger individuals, so the data concerning healthy age-matched/'older' individuals on the cross-slope is also worth noting.

Overall, though the participants did not perceive the represented conditions to be particularly difficult, as indicated by their responses in the posttrial questionnaire, evidence from their gait (i.e., such as increased RMS values) as well as the identification of main effects seem to indicate that at least some challenge did exist, especially in the case of added surface irregularity. The results of this study will provide verification of gait adaptations in the 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.

4.2 Limitations

The limitations of this study included that the population size might not have been adequate to detect all significant differences between the representative groups due to the complexity of the combinations of conditions being tested as well as the complexity of the resulting statistical models. In addition, due to the energetic cost of walking on uneven terrain and the temporal length of the trials, some of the participants with PD became somewhat fatigued and/or the effects of their medication began to wear off before they completed all of their trails.[47] This might have introduced error in the final comparisons of the surfaces that the randomization of the surfaces could not prevent. Furthermore, participants were asked not to alter their gait in order to achieve the clean force plate strikes that were necessary to mark a good trial, however, the force plates were conspicuous (especially during the flat surface condition) and thus some of the participants might have unintentionally changed their stepping pattern when on/near the force plates. This in turn might have introduced additional error in the data. Finally, one last limitation was that the layout of the force plates was not ideal for collecting force data from the participants with PD because those who exhibited shuffling gait could not achieve a step length long enough to step on force plates separately. For this reason and because of the fact that this kinetic data could not be used in the Treadport (due to its lack of a ground reaction force measurement system), kinetic data were not the focus of this thesis.

4.3 Future Work

Future work will include using these data to verify that simulated terrains in the Treadport (similar to those in this study) elicit the same characteristic gait behavior as physical environments, so that the Treadport may then be used for rehabilitative work in improving the gait of those with PD on such terrains. Additional work will also include interpreting the results of the data that were collected, but not used in the focus of this paper (i.e., usable kinetic data, HY participant data, dual task data).

APPENDIX A

CONSENT DOCUMENT

Consent Document

BACKGROUND

You are being asked to take part in a multi-part research study. Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with friends and relatives if you wish. Ask the research doctor or staff if there is anything that is not clear or if you would like more information. Take time to decide whether or not to volunteer to take part in this research study.

The purpose of the study is to collect information on how people normally navigate obstacles and changes in terrain such as climbing stairs, moving from seated to standing positions, walking on gravel, etc. so we can understand how to graphically represent this terrain in virtual environments and develop new technology and training procedures to improve stability and reduce the chance of falls.

STUDY PROCEDURES

There are 3 major parts to the study. You are being asked to agree to the parts of the study for which you are eligible, and they should be clearly marked with a checkmark (***If you do not see a checkmark next one or more parts, or are unsure which part of the consent document is applicable to you, please see one of the research staff immediately before proceeding.***).

[_____] PART 1 - DEVELOPMENT OF THE PHYSICAL ENVIRONMENT

The purpose of this part of the study is to determine and characterize aspects of your environment that you find challenging to navigate. Once we identify these activities, physical representations of these situations will be created in the Motion Analysis Core Facility (MOCAP) and Ergonomics and Safety (E & S) Laboratory for two purposes: (1) To evaluate the validity of the simulated environment of the lab and to collect movement data during these mobility challenging activities, and (2) To develop a virtual reality environment that simulates these real-world challenges.

To accomplish this, you may participate in a recorded interview with a questionnaire to define common environments and situations that cause mobility challenges for you. For example, do you trip and stumble sometimes when you walk on an uneven sidewalk? A physical environment in the laboratory will be constructed that includes the common themes identified from the interview. For participants with Parkinson disease that are already using dopamine replacement medications, all testing will be done within 1-2 hours of taking the regular dosage of dopamine replacement medications to assure medication levels are consistent.

Part one of this study will take place in two separate locations on the university campus. At both locations, you can expect the following progression of events:

- You will enter one of the motion analysis labs.
- If applicable, you will be interviewed and a questionnaire will be completed about your self-report of difficulty in various mobility challenging environments.
- Next, you will be provided with a black tight fitting shirt and shorts for testing.
- Demographic and body measurement data will be collected from you.
- Reflective markers will be placed on you.

- You will be fitted with a ceiling mounted fall harness and support system to prevent falls to the ground.
- You will be directed to stand on a special square on the floor or treadmill called a force platform.
- Next, you will be asked to complete several tasks such as walking, jumping, standing up from sitting, climbing stairs, rising up on your toes, and remaining upright when your balance is challenged. You will also be asked to engage in a recorded speech task during some of these activities.
- You will be asked to perform 5 trials of each task.
- After the tasks are complete, the markers will be removed and you can change back into your street clothes.
- Additional questions and assessments will be made using standard questionnaires to assess other factors that may be related to balance, and perceptions of difficulty during walking and interactions with your environment. For example, we will ask you to remember a list of five things and repeat them in order back to the researcher.

[______] PART 2 - SHOE DEVELOPMENT

A new form of insole, or "Smart Shoe" has been created and rigorously tested in a laboratory testing fixture. Our purpose is to evaluate the changes in movement while wearing the smart shoe compared to not wearing it, and obtain feedback from you as a user to evaluate and improve smart shoe designs and identify features that provide the most benefit for providing assistance during mobility challenging activities.

Testing will include the functional gait assessment (FGA), the 6 minute walk test (6MWT), and gait analysis in a physical environment presented in the MOCAP, E&S Labs. The following is the progression of events you should expect in Part 2:

- You will enter one of the motion analysis labs.
- Next, you will be provided with a black tight fitting shirt and shorts for testing. A private changing room will be provided.
- You will be given instructions about the Smart Shoes and what to expect while wearing them.
- Demographic and body measurement data will be collected from you.
- Reflective markers will be placed on you.
- You will be fitted with a ceiling mounted fall harness and support system to prevent falls to the ground.
- You will be directed to stand on a special square on the floor called a force platform.
- Next, you will be asked to complete several tasks such as walking, jumping, standing up from sitting, climbing stairs, rising up on your toes, and remaining upright when your balance is challenged.
- You will be asked to perform 5 trials of each task.
- After the tasks are complete, the markers will be removed and you can change back into your street clothes.
- Additional questions and assessments will be made using standard questionnaires to assess other factors that may be related to balance, and perceptions of difficulty during walking and interactions with your environment. For example, we will ask you to remember a list of five things and repeat them in order back to the researcher.

- This completes this part of the study.

[______] PART 3 - VIRTUAL REALITY TRAINING

The purpose of this part of the study is to learn more about the potential benefits of training on a treadmill and virtual environment system known as the Treadport Active Wind Tunnel-Terrain Display Simulator (TPAWT-TDS). Conventional training is often limited and becomes even more complicated due to weather or being able to simulate an environment accurately in a laboratory setting. There is evidence to suggest that training activities in virtual reality may improve motor function and balance recovery after a minor perturbation. You are being asked to participate in a study to determine if the immersive virtual environment system and a Smart Shoe developed to provide realistic sensations of walking on irregular terrains in the TPAWT-TDS is more beneficial as a training device than training without VR and Smart Shoe technology. Pretesting will include the functional gait assessment (FGA), the 6 minute walk test (6MWT), gait analysis and biomechanical analysis in a physical environment presented in the MOCAP and E&S Labs. Pretesting should require approximately 2 and a half hours of your time. The following is the progression of events you should expect for pretesting:

- You will enter the MOCAP or E&S lab.
- Next, you will be provided with a black tight fitting shirt and shorts for testing.
- Demographic and body measurement data will be collected from you.
- Reflective markers will be placed on you.
- You will be fitted with a ceiling mounted fall harness and support system to prevent falls to the ground. You will be directed to stand on a special square on the floor called a force platform.
- Next, you will be asked to complete several tasks such as walking, jumping, standing up from sitting, climbing stairs, rising up on your toes, and remaining upright when your balance is challenged.
- You will be asked to perform 5 trials of each task.
- After the tasks are complete, the markers will be removed and you can change back into your street clothes.
- Additional questions and assessments will be made using standard questionnaires to assess other factors that may be related to balance, and perceptions of difficulty during walking and interactions with your environment. For example, we will ask you to remember a list of five things and repeat them in order back to the researcher.

Following pretesting, you will undergo training. Training will be performed in the TPAWT-TDS. The treatment regimen will last 6 weeks (3x/wk) for a total of 18 sessions. The duration of each session will be approximately 45 minutes with a 5 minute warm-up period of walking on the treadmill without VR or haptic display. In addition, you will be given up to 5, three minute rest breaks, as needed. During this study your movement will be evaluated and recorded. During training you will be presented with various virtual terrains that represent mobility challenging environments. You will be tethered with a safety device during all trials. The following is the progression of events you should expect during each training regimen:

- You will enter the TPAWT-TDS.
- Next, you will be provided with a black tight fitting shirt and shorts for testing. A private changing room will be provided.
- Demographic and body measurement data will be collected from you.

- Reflective markers will be placed on you.
- Next, you will be tethered to the system with a support to prevent falls to the ground and warm up on the treadmill with the virtual environment for 5 minutes
- Following warm up, a training session lasting 45 minutes where you will be presented with virtual terrain and a realistic virtual representation of a common setting (for example, walking on a sidewalk with uneven slabs, or walking from a room with wood flooring to a carpeted floor), during which you will experience some mobility challenging conditions.
- After the training session, the markers will be removed and you can change back into your street clothes.

Following training you will be scheduled for a final post-testing appointment at the MOCAP and E&S labs. Post-testing will include the functional gait assessment (FGA), the 6 minute walk test (6MWT), gait analysis and biomechanical analysis in a physical environment presented in the MOCAP and E&S Labs. Post-testing should require approximately two and a half hours of your time. The following is the progression of events you should expect:

- You will enter the MOCAP or E&S lab.
- Next, you will be provided with a black tight fitting shirt and shorts for testing.
- Demographic and body measurement data will be collected from you.
- Reflective markers will be placed on you.
- You will be directed to stand on a special square on the floor called a force platform.
- Next, you will be asked to complete several tasks such as walking, jumping, standing up from sitting, climbing stairs, rising up on your toes, and remaining upright when your balance is challenged.
- You will be asked to perform 5 trials of each task.
- After the tasks are complete, the markers will be removed and you can change back into your street clothes.
- This completes this part of the study.

RISKS

For this study, markers are attached to the skin with hypoallergenic tape. There may be some minor discomfort experienced when the small pieces of tape are removed from your skin. This is similar to removing very small Band-Aids. In addition, because of the need for you to perform balance activities, the risk for falling is increased. However, you will be supervised at all times by a researcher with experience in fall prevention and you will also be attached to a fall restraint tether secured to the ceiling. In the event of an unprotected fall resulting in an injury, first aid will be provided. If additional medical care is required, the appropriate emergency medical services will be provided.

RESEARCH RELATED INJURY

If you are injured from being in this study, medical care is available to you at the University of Utah Medical Center, as it is to all sick or injured people. The University of Utah has not set aside any money to pay the costs for such care. The University will work with you to address costs from injuries. Costs would be charged to you or your insurance company (if you have insurance), to the study sponsor or other third party (if applicable), to the extent those parties are responsible for paying for medical care you receive. Since this is a research study, some health insurance plans may not pay for the costs. By signing this consent form you are not giving up your right to pursue legal action against any parties involved with this research.

The University of Utah is a part of the government. If you are injured in this study, and want to sue the University or the doctors, nurses, students, or other people who work for the University, special laws may apply. The Governmental Immunity Act of Utah is a law that controls when a person needs to bring a claim against the government, and limits the amount of money a person may recover. See sections 63G -7-101 to -904 of the Utah Code.

BENEFITS
There are no direct benefits to you from your taking part in this study. We hope that the information we gain from this study will help us understand and discover effective treatments to improve balance and decrease the risk of falling for individuals with mobility challenging disorders such as Parkinson disease.

ALTERNATIVE PROCEDURES
If you do not want to take part in the study, you can choose not to participate. There are no alternate procedures offered.

CONFIDENTIALITY
We will keep all research records that identify you private to the extent allowed by law. Records about you will be kept locked in filing cabinets or on computers protected with passwords. Only those who work with this study will be allowed access to your information. Results of the study may be published; however, your name and other identifying information will be kept private. However, if we learn about actual or suspected abuse, neglect, or exploitation of a disabled or elderly person, we will report that to the proper authorities.

The nature of this study requires that we record video to evaluate activities and quantify biomechanics. These videos are used for reference and will only be used for educational reasons and at research conferences. Your name will not be used, and the face of the images will be blurred when possible, but they will never have your name associated with their images. During your movement trials, a reference video will be recorded to evaluate motion data integrity and as a quality check.
Portions of this study (part 1 only) require audio recordings for reference and evaluation. The video and audio files will only be stored until all analyses are completed for the study. Only qualified research personnel will have access to these video and audio files s and access will be controlled on encrypted, password-protected computers. Measures will be taken to prevent identifiability when possible by blurring identifying features (face), and using ID numbers instead of names on audio recordings. There may be instances in an educational or teaching environment when this is not possible.

Please indicate by initialing below that you understand that images and audio recordings of you may be used in presentations for teaching and research purposes, but all efforts will be made to prevent identifiability.

Initial _____________

PERSON TO CONTACT
If you have any questions, complaints or concerns about this study, or if you feel you have been harmed as a result of participation, you can contact and of the research staff included in the following list. If you need to contact someone for an injury that resulted from being in this study, please call Dr. Bo Foreman at 801.581.3496 or Dr. Lee Dibble at 801.581.4637 during business hours Monday through Friday. Dr. Foreman can also be reached after hours by calling 801.243.9111. If you need to speak with any of the other investigators related to this study their contact information is listed below:

- Mark Minor (PI): 801.587.7771
- Andrew Merryweather: 801.581.8118
- John Hollerbach: 801.585.6978

INSTITUTIONAL REVIEW BOARD:
Contact the Institutional Review Board (IRB) if you have questions regarding your rights as a research participant. Also, contact the IRB if you have questions, complaints or concerns which you do not feel you can discuss with the investigator. The University of Utah IRB may be reached by phone at (801) 581-3655 or by e-mail at irb@hsc.utah.edu.

RESEARCH PARTICIPANT ADVOCATE: You may also contact the Research Participant Advocate (RPA) by phone at (801) 581-3803 or by email at participant.advocate@hsc.utah.edu.

VOLUNTARY PARTICIPATION
It is up to you to decide whether or not to take part in this study. If you decide to take part you are still free to withdraw at any time and without giving a reason. Refusal to participate or the decision to withdraw from this study will involve no penalty or loss of benefits to which you are otherwise entitled. If you don't take part, you can still receive all standard care that is available to you. This will not affect the relationship you have with the research staff.

UNFORESEEABLE RISKS
In addition to the risks listed above, you may experience a previously unknown risk or side effect.

COSTS AND COMPENSATION TO PARTICIPANTS
You will be compensated for your time and participation in this study. You will not be charged, nor will your insurance company be charged, for any test or visit that is completed solely for the purpose of this study. Since you will be paid for participating in this study, it is necessary for us to collect your Social Security Number. You will provide this information for a Federal W-9 Form that is filed with our Accounts Payable department. Accounts Payable will have limited access to the study information (e.g. the name of the study) for payment purposes. The amount you receive for taking part in this study will be turned into the Internal Revenue Service (IRS) as taxable income. You can choose not to provide us with your Social Security Number for this form and still participate in this study; however we will not be able to pay you as outlined in this consent form.

NUMBER OF PARTICIPANTS
We expect to enroll a total of 80 participants at the University of Utah (40-Part 1, 10-Part 2, and 30-Part 3).

CONSENT
By signing this consent form, I confirm I have read the information in this consent form and have had the opportunity to ask questions. I will be given a signed copy of this consent form. I voluntarily agree to take part in this study.

I agree to take part in (circle parts of the study you agree to participate in):

- **Part 1**
- **Part 2**
- **Part 3**

of this research study and authorize you to use and disclose health information about me for this study, as you have explained in this document.

____
Participant's Name

__________________________ _____________
Participant's Signature Date

____
Name of Person Obtaining Consent

__________________________ _____________
Signature of Person Consent Date

APPENDIX B

FALL HISTORY QUESTIONNAIRE – PRELIMINARY QUESTIONNAIRE

Fall History Questionnaire

ID:_______________

Directions: Please answer the following questions about yourself by marking an X in front of the appropriate answer. For your information a fall is defined below:

- A **fall** is 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.
- A **near fall** is a sudden loss of balance that does not result in a fall or other injury. This can include a person who slips, stumbles or trips but is able to regain control prior to falling.

IN THE PAST YEAR:	
How often have you had a **fall(s)**:	How often have you had a **near fall(s)**:
( ) None ( ) 1 time ( ) 2 times ( ) 3 times ( ) > 3 times (Please estimate number):_________	( ) None ( ) 1 time ( ) 2 times ( ) 3 times ( ) > 3 times (Please estimate number):_________

*******If you have NOT had a fall or near fall, please STOP here and contact a member of the research team*******

IN THE 6 MONTHS:	
How often have you had a **fall(s)**:	How often have you had a **near fall(s)**:
( ) None ( ) 1 time ( ) 2 times ( ) 3 times ( ) > 3 times (Please estimate number):_________	( ) None ( ) 1 time ( ) 2 times ( ) 3 times ( ) > 3 times (Please estimate number):_________

IN THE PAST MONTH:	
How often have you had a **fall(s)**:	How often have you had a **near fall(s)**:
( ) None ( ) 1 time ( ) 2 times ( ) 3 times ( ) > 3 times (Please estimate number):_________	( ) None ( ) 1 time ( ) 2 times ( ) 3 times ( ) > 3 times (Please estimate number):_________

Where have you experienced fall(s) INSIDE your home or residence?:

- ( ) On level surface
- ( ) Getting out of bed
- ( ) Standing from chair or lower surface
- ( ) Lowering to sit on chair or lower surface
- ( ) Using the shower
- ( ) Using the bath
- ( ) Using the toilet
- ( ) Walking up the stairs
- ( ) Walking down the stairs
- ( ) Crossing a threshold
- ( ) On a rug or mat
- ( ) Stepping over an obstacle on the floor (e.g. toys, pets, books, clothes)
- ( ) Going from one floor surface (e.g. hardwood) to another floor surface (e.g. carpet)
- ( ) Turning

Where have you experienced fall(s) OUTSIDE your home or residence?:

- ( ) Walking up a step(s)
- ( ) Walking down a step(s)
- ( ) On an escalator
- ( ) On a moving walkway
- ( ) Entering or exiting a building
- ( ) Uneven sidewalk or walkway
- ( ) On a curb or gutter
- ( ) Getting out of a vehicle
- ( ) On a grass surface
- ( ) On a gravel surface
- ( ) On a dirt surface
- ( ) On an asphalt surface
- ( ) On an icy/snowy surface
- ( ) On a wet surface
- ( ) Going from one walking surface to another
- ( ) Walking up a ramp
- ( ) Walking down a ramp

What factors contribute to your fall(s)?:

- ( ) I tripped
- ( ) I slipped
- ( ) I lost my balance
- ( ) My legs gave way
- ( ) I was faint
- ( ) I felt dizzy
- ( ) I was frozen due to Parkinson disease
- ( ) I was startled
- ( ) I am not sure
- ( ) Other, please describe:

What is the most common cause of your fall(s)?:

- ( ) I tripped
- ( ) I slipped
- ( ) I lost my balance
- ( ) My legs gave way
- ( ) I was faint
- ( ) I felt dizzy
- ( ) I was frozen due to Parkinson disease
- ( ) I was startled
- ( ) I am not sure
- ( ) Other, please describe:

Where have you experienced near fall(s) INSIDE your home or residence?:

• ( ) On level surface • ( ) Getting out of bed • ( ) Standing from chair or lower surface • ( ) Lowering to sit on chair or lower surface • ( ) Using the shower • ( ) Using the bath • ( ) Using the toilet • ( ) Walking up the stairs • ( ) Walking down the stairs	• ( ) Crossing a threshold • ( ) On a rug or mat • ( ) Stepping over an obstacle on the floor (e.g. toys, pets, books, clothes) • ( ) Going from one floor surface (e.g. hardwood) to another floor surface (e.g. carpet) • ( ) Turning

Where have you experienced near fall(s) OUTSIDE your home or residence?:	
• ( ) Walking up a step(s) • ( ) Walking down a step(s) • ( ) On an escalator • ( ) On a moving walkway • ( ) Entering or exiting a building • ( ) Uneven sidewalk or walkway • ( ) On a curb or gutter • ( ) Getting out of a vehicle • ( ) On a grass surface	• ( ) On a gravel surface • ( ) On a dirt surface • ( ) On an asphalt surface • ( ) On an icy/snowy surface • ( ) On a wet surface • ( ) Going from one walking surface to another • ( ) Walking up a ramp • ( ) Walking down a ramp
What factors contribute to your fall(s)?:	
• ( ) I tripped • ( ) I slipped • ( ) I lost my balance • ( ) My legs gave way • ( ) I was faint • ( ) I felt dizzy • ( ) I was frozen due to Parkinson disease • ( ) I was startled • ( ) I am not sure	• ( ) Other, please describe:

What is the most common cause of your near fall(s)?:	
• ( ) I tripped **• ( ) I slipped** **• ( ) I lost my balance** **• ( ) My legs gave way** **• ( ) I was faint** **• ( ) I felt dizzy** **• ( ) I was frozen due to Parkinson disease** **• ( ) I was startled** **• ( ) I am not sure**	
Has the level of lighting inside or outside contributed to your fall(s) or near fall(s)?	**( ) YES ( ) NO**
Does your choice of footwear (or lack of) contribute to your fall(s) or near fall(s)?	**( ) YES ( ) NO**

What type of shoes do you usually wear at home?
What type of shoes do you usually wear when you go out?
Do you wear orthotics in your shoes?

APPENDIX C

FALL PROTECTION SYSTEM SAFETY ANALYSIS RESULTS

O & S H A									
Item#	**Task**	**Potentially Hazardous Condition**	**Cause**	**Effect**	**Freq**	**Sev**	**Det**	**Concern Level**	**Recommendation**
1	Put on harness	Harness too loose/too large	Harness fitted improperly	Fall out of harness scenario	3	3	1	9	Worker training; Redundant, Simpler design
2	Get on track/ Go up stairs	Trips and falls	Existing natural hazard	Potential participant injury	4	3	1	12	Stairs adequately wide and high; Ensure presence of rail support; Personnel assistance when necessary
3	Clip into the system	Clip not shut and oriented along major axis	Human error	Failure of system to catch a fall	2	3	2	12	Worker training
4	Walk	Trips and falls	Terrain; Participant loss of motor control or lack of attention	Potential participant injury	4	1	1	4	Ensure safest, Most comfortable catch possible
5	Unclip and get off the track	Trips and falls	Existing natural hazard	Potential participant injury	4	3	1	12	Same as getting on track

F M E A									
ID #	**Item**	**Failure Mode**	**Failure Cause**	**Failure Effect**	**Target**	**Risk Assessment**			**Required Actions/Remarks**
						Sev	**Prob**	**Risk**	
1	**Clamping System**								
1.1	Eyelet adapter	End Fracture	High shear stresses, Excessive loading	Partial loss of beam support, Partial loss of fall protection, Risk of less controlled and more painful catch during fall	P, E	1	D	3	Provide training: competency in fall protection and system operations
		Thread Wear	Defective materials, Excessive loading	Partial loss of beam support, Partial loss of fall protection, Risk of less controlled and more painful catch during fall	P, E	1	D	3	Perform background check on reliability of parts' suppliers/manufacturers; Provide training: competency in fall protection and system

									operations; Perform regular maintenance checks
1.2	Threaded Rod	Thread Stripping	Defective materials, Excessive loading	Partial loss of beam support, Partial loss of fall protection, Risk of less controlled and more painful catch during fall	P, E	1	D	3	Perform back ground check on reliability of parts' suppliers/ manufacturers; Provide training: competency in fall protection and system operations; Perform regular maintenance checks
1.3	Washer	Fracture	High shear stresses, Excessive loading	Partial beam instability	P, E	3	E	3	Provide training: comp

									etency in fall protection and system operations
		Thread Wear	Excessive loading	Partial beam instability	P, E	3	E	3	
		Slipping out	High shear stresses, Excessive Loading	Partial beam instability	P, E	3	E	3	Provide training: competency in fall protection and system operations
1.4	Nut	Fracture	High shear stresses, Excessive loading	Partial beam instability	P, E	2	D	3	Provide training: competency in fall protection and system operations
		Thread Wear	Defective materials, Excessive loading	Partial beam instability	P, E	2	D	3	Perform background check on reliability of parts' suppliers/

									manufacturers; Provide training: competency in fall protection and system operations; Perform regular maintenance checks
		Slipping out	High shear stresses, Excessive loading	Partial beam instability	P, E	2	D	3	Provide training: competency in fall protection and system operations
1.5	Clamps	Flange Splay Opens	Defective materials, Excessive loading	Partial loss of beam support, Partial loss of fall protection, Risk of less controlled and more painful catch during fall2	P, E	2	E	3	Perform background check on reliability of parts' suppliers/ manu

									facturers; Provide training: competency in fall protection and system operations
		Flange Bolt Joint Cracks open	High shear stresses, Excessive loading	Partial loss of beam support, Partial loss of fall protection, Risk of less controlled and more painful catch during fall	P, E	2	E	3	Perform background check on reliability of parts' suppliers/ manufacturers; Provide training: competency in fall protection and system operations; Perform regular maintenance check

									s
1.6	Spacer	Cracks	Material failure	No Significant Effect on Fall Protection	E	3	D	3	Perform background check on reliability of parts' suppliers/ manufacturers
1.7	Structural Roof Beams	Structural Collapse	Severe weather causes, Building collapse	Total System Failure	P, E, Envir	1	F	3	Very low probability, so no recommended action thought necessary
2	**Unistrut System**								
2.1	Trolley	Axel Failure	Metal Fatigue, Defective materials, Excessive loading	Risk of less controlled, more painful catch during fall, Complete loss of fall protection	P, E	1	D	2	Perform background check on reliability of parts' suppliers/ manufacturers; Provide training:

									competency in fall protection and system operations; Perform regular maintenance checks
		Bearing Disengagement	Metal fatigue, Defective materials, Manufacturing defects, Excessive loading	Risk of less controlled, more painful catch during fall, Complete loss of fall protection	P, E	1	D	2	Perform background check on reliability of parts' suppliers/ manufacturers; Provide training: competency in fall protection and system operations; Perform regular maint

									enance checks
		Clip Failure	Metal fatigue, Defective materials, Manufacturing defects, Excessive loading	Risk of less controlled, more painful catch during fall, Complete loss of fall protection	P, E	1	D	2	Perform back ground check on reliability of parts' suppliers/ manufacturers; Provide training: competency in fall protection and system operations; Perform regular maintenance checks
2.2	Rail	Beam Splay/Failure (top/bottom)	Defective materials, Manufacturing defects, Non compliance with system limits, Excessive loading	Risk of less controlled, more painful catch during fall, Complete loss of fall protection	P, E	1	D	2	Perform back ground check on reliability of parts' suppl

									iers/ manufacturers
		Beam to beam attachment failure	Defective materials, Manufacturing defects, Excessive loading, Non compliance with system limits	Complete loss of fall protection, Trolley slips out, whole beam system comes down	P, E	1	E	3	Perform back ground check on reliability of parts' suppliers/ manufacturers
3	**Harness System**								
3.1	Harness	Webbing	Defective materials, Manufacturing defects	Risk of less controlled and more painful catch during fall, Complete loss of fall protection	P, E	1	D	2	Perform back ground check on reliability of parts' suppliers/ manufacturers
		Buckle failure	Defective materials, Manufacturing defects	Risk of less controlled and more painful catch during fall, Complete loss of fall protection	P, E	1	D	2	Perform back ground check on reliability of parts' suppliers/ manufacturers

		Improper use or attachment failure	Human error, Improper harness sizing	Risk of less controlled and more painful catch during fall, Complete loss of fall protection	P, E	1	C	1	Training: competency in fall protection and system operations
3.2	Bungee Cord	Cord Failure	Defective materials, Manufacturing defects, Non compliance with system limits	Risk of less controlled and more painful catch during fall, Complete loss of fall protection	P, E	1	D	2	Perform background check on reliability of parts' suppliers/ manufacturers; Provide training: competency in fall protection and system operations
		Attachment Failure	Defective materials, Manufacturing defects, Human error during lifetime use, Non compliance with system	Risk of less controlled and more painful catch during fall, Complete loss of fall protection	P, E	1	D	2	Perform background check on reliability of parts suppl

			limits						iers/ manu factur ers; Provi de traini ng: comp etenc y in fall prote ction and syste m opera tions
		Failure due to use beyond rated number of falls	Human error during lifetime use, Non compliance with system limits	Risk of less controlled and more painful catch during fall, Complete loss of fall protection	P, E	1	C	1	Provi de traini ng: comp etenc y in fall prote ction and syste m opera tions
4	**Hand Rail System**								
4.1	Hand Rail	Collapse, Detachme nt	Faulty Materials, Manufactur ing defects, Excessive loading	Loss of stability to participant – potential to fall / risk	P, E	2 OR 3	D	3	Perfo rm back groun d check on reliab ility of parts' suppl iers/ manu factur ers; Provi de traini

									ng: competency in fall protection and system operations

APPENDIX D

POSTTRIAL QUESTIONNAIRE

POST-TRIAL ERGO QUESTIONNAIRE

Participant ID:__________

1. How difficult was it to maintain stability on each of the terrains during the single and dual tasks? (on a scale of 1-5 where 1 corresponds to 'not difficult at all' and 5 corresponds to 'very difficult')
   a. Flat, no rocks: single_______ dual_______
   b. Flat, rocks: single_______ dual_______
   c. 10□ camber, no rocks: single_______ dual_______
   d. 10□ camber, rocks: single_______ dual_______

2. What additional conditions and/or tasks might have made the most difficult terrain/camber conditions even more difficult if the dual task used during today's trials hadn't been implemented?
   ( ) Regulated pace
   ( ) Poor lighting
   ( ) Other:
   ____
   ____
   ____
   ____
   ____

3. At any point did you experience a loss of balance which you felt could have resulted in a fall if fall protection (i.e. a harness/tether and handrails) hadn't been provided? ( )yes ( )no
   a. If yes, under which conditions did this occur? (see question 1 for list of trial conditions)
   ____
   ____
   ____
   ____
   ____

4. In real life have you encountered similar terrains to those encountered today? ( )yes ( )no
   a. If yes, explain where and how similar they compared to what was seen today.
   ____
   ____
   ____
   ____
   ____

5. ***(For participants without PD):***
   a. Dominant leg/foot (i.e. which would you kick a soccer ball with)? ( )right ( )left

   b. Did your dominant side make it easier to travel in one direction in comparison to the other in the off camber condition? ( )yes ( )no

i. If yes, which direction was easier?
( ) Away from the computer
( ) Towards the computer

6. ***(For participants with PD):***

Definitions:
A **fall** is 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.
A **near fall** is a sudden loss of balance that does not result in a fall or other injury. This can include a person who slips, stumbles or trips but is able to regain control prior to falling.

a. Dominant leg/foot (i.e. which would you kick a soccer ball with)? ( )right ( )left

b. Which leg/foot is more affected by Parkinson disease? ( )right ( )left

c. Did your more affected side make it more difficult to travel in one direction in comparison to other on the 10^{o} camber condition? ( )yes ( )no
   i. If yes, in which direction?
   ( ) Away from the computer
   ( ) Towards the computer

d. In the past 6 months how many times have you **fallen**? __________

e. In the past 6 months how many times have you had a **near fall**? __________

f. Did you incur any injuries as a result of your falls/near falls? ( )yes ( )no
   i. If so, please describe the nature and severity of the injuries?
   ____
   ____
   ____
   ____
   ____

g. Where have you experienced falls/near falls outside of your house?
( ) Walking up a step(s)
( ) Walking down a step(s)
( ) On an escalator
( ) On a moving walkway
( ) Entering or exiting a building
( ) Uneven sidewalk or walkway
( ) On a curb or gutter
( ) Getting out of a vehicle
( ) On a grass surface
( ) On a gravel surface

( ) On a dirt surface
( ) On an asphalt surface
( ) On an icy/snowy surface
( ) On a wet surface
( ) Going from one walking surface to another
( ) Walking up a ramp
( ) Walking down a ramp
( ) Other:
____
____
____
____
____

h. What are the most common causes of your outside falls/near falls?
( ) I tripped
( ) I slipped
( ) I lost my balance
( ) My legs gave way
( ) I was faint
( ) I felt dizzy
( ) I was frozen due to Parkinson disease
( ) I was startled
( ) I am not sure
( ) Other:
____
____
____
____
____

i. Where have you experienced falls/near falls inside your house?
( ) On level surface
( ) Getting out of bed
( ) Standing from chair or lower surface
( ) Lowering to sit on chair or lower surface
( ) Using the shower
( ) Using the bath
( ) Using the toilet
( ) Walking up the stairs
( ) Walking down the stairs
( ) Crossing a threshold
( ) On a rug or mat
( ) Stepping over an obstacle on the floor (e.g. toys, pets, books, clothes)
( ) Going from one floor surface (e.g. hardwood) to another floor surface (e.g. carpet)
( ) Turning
( ) Other:

____
____
____
____
____

j. What are the most common causes of your inside falls/near falls?
( ) I tripped
( ) I slipped
( ) I lost my balance
( ) My legs gave way
( ) I was faint
( ) I felt dizzy
( ) I was frozen due to Parkinson disease
( ) I was startled
( ) I am not sure
( ) Other:
____
____
____
____
____

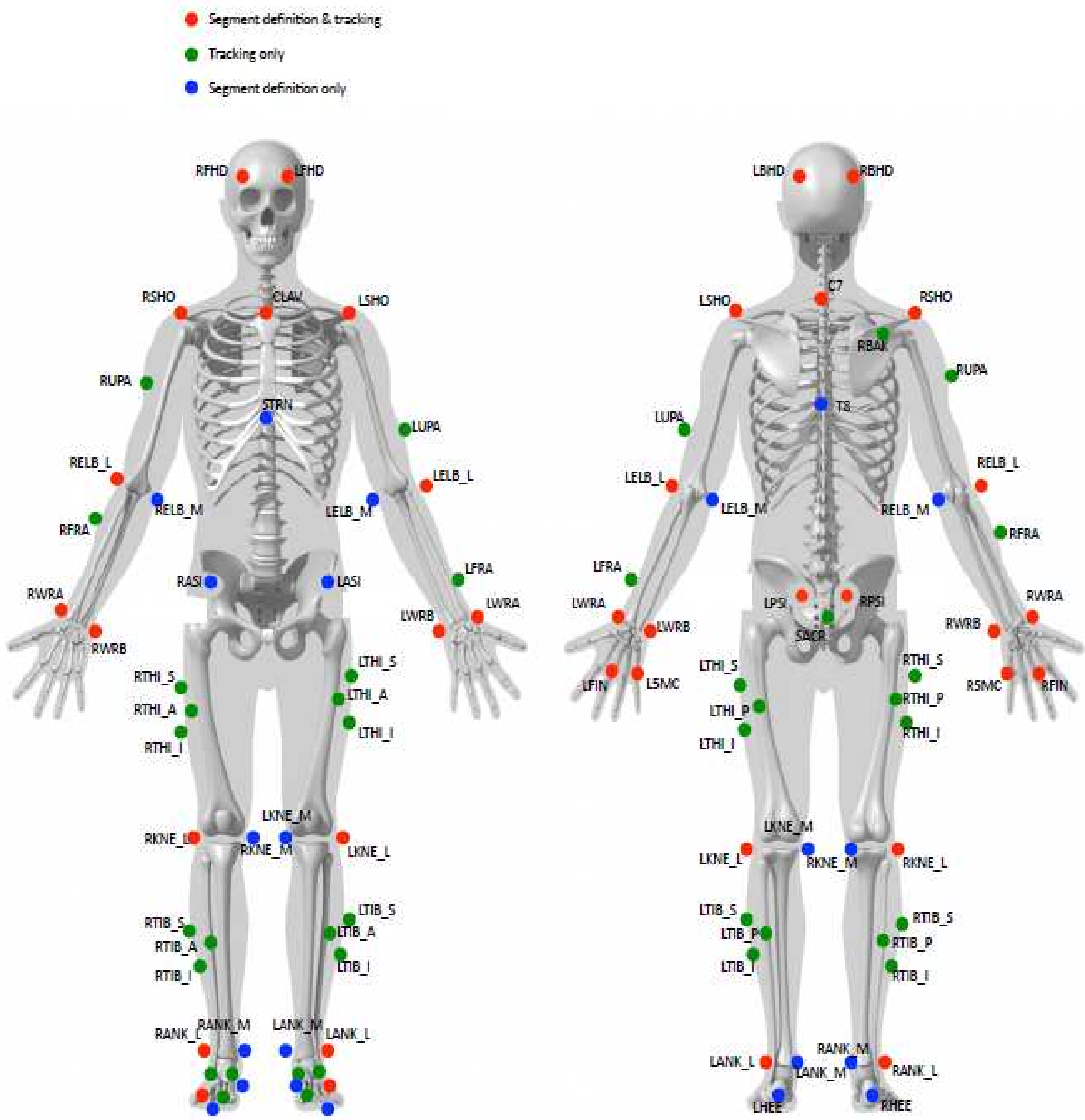
k. Has the level of lighting specifically contributed to your falls/near falls? ( )yes ( )no

l. Has your choice of footwear specifically contributed to your falls/near falls? ( )yes ( )no

7. Additional Comments
____
____
____
____
____

APPENDIX E

SUBJECT MARKERSET AND FORCEPLATE MARKERSET


Segment definition & tracking
Tracking only
Segment definition only
RFHD
LFHD
RSHO
CLAV
LSHO
RUPA
STRN
LUPA
RELB_L
RELB_M
LELB_M
LELB_L
RFRA
RASI
LASI
LFRA
RWRA
RWRB
LWRB
LWRA
RTHI_S
RTHI_A
RTHI_I
LTHI_S
LTHI_A
LTHI_I
LKNE_M
RKNE_L
RKNE_M
LKNE_L
RTIB_S
RTIB_A
RTIB_I
LTIB_S
LTIB_A
LTIB_I
RANK_L
RANK_M
LANK_M
LANK_L
LBHD
RBHD
C7
LSHO
RSHO
RBAK
RUPA
LUPA
T8
LELB_L
LELB_M
RELB_M
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LFRA
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LWRB
LPSI
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SACR
RWRA
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LFIN
L5MC
R5MC
RFIN
LTHI_S
LTHI_P
LTHI_I
RTHI_S
RTHI_P
RTHI_I
LKNE_M
LKNE_L
RKNE_M
RKNE_L
LTIB_S
LTIB_P
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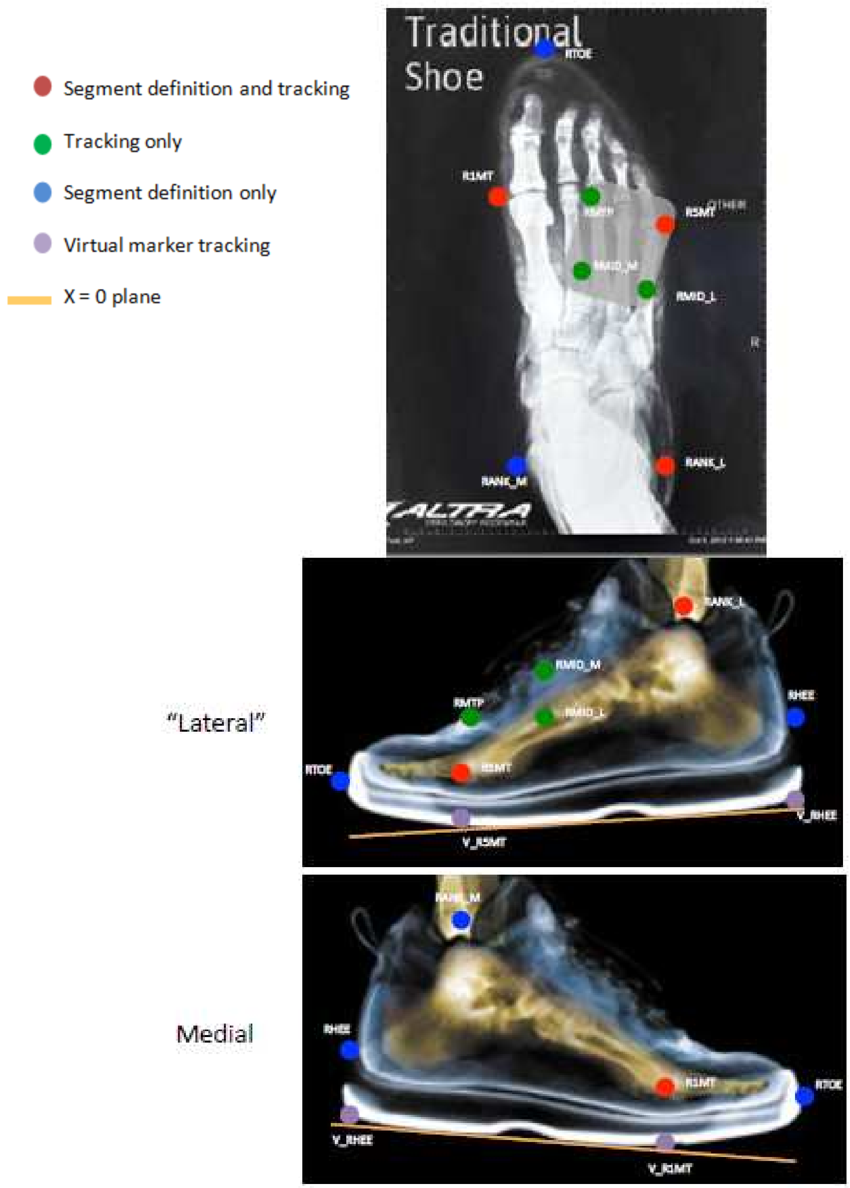
Segment definition and tracking
Tracking only
Segment definition only
Virtual marker tracking
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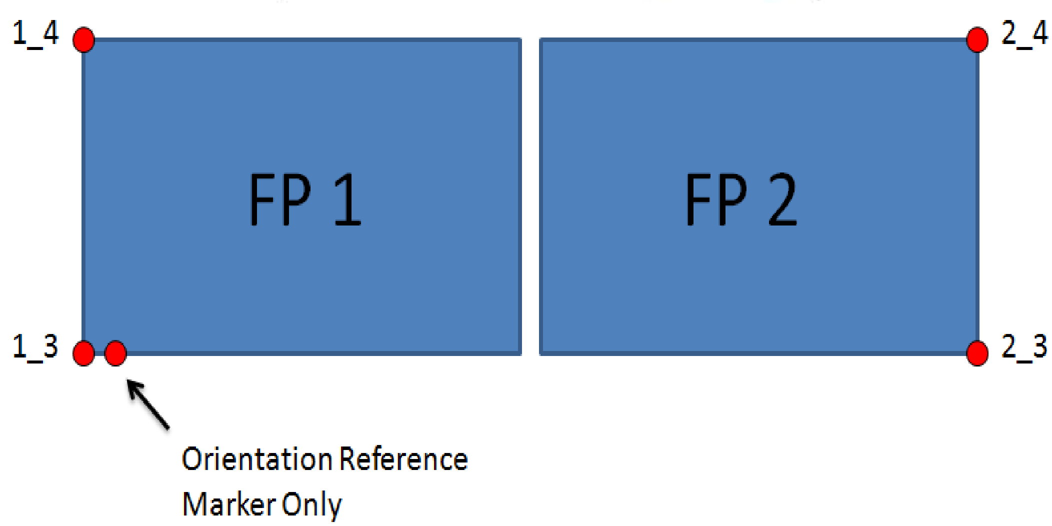
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Orientation Reference
Marker Only

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