Augmenting Virtual Reality Terrain Display with Smart Shoe Physical Rendering: A Pilot Study

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***Abstract*—Haptic terrain rendering is limited in existing Virtual Reality (VR) systems. This article describes integration of the Smart Shoe (SS) for physical terrain display with the TreadPort VR system. The SS renders both gross sloped terrain and subtle sensations of stepping on small objects or uneven surfaces. The TreadPort projects terrain on the floor and the SS renders terrain that the user steps upon via motion tracking. The research is motivated towards eventually providing gait training for people with Parkinson's Disease (PD), hence this work presents a pilot study evaluating haptic terrain rendering with healthy elderly and PD participants wearing the SS within the TreadPort. Uneven cobblestone surfaces are rendered by the SS as the participant steps on their graphical representation in VR. While posthoc analysis shows the study is underpowered, kinematic and spatiotemporal results derived from motion capture data demonstrates kinesthetic response (e.g., increased maximum ankle angle and minimum toe clearance, reduced minimum ankle angle and knee angle) provided by the SS. Questionnaire data shows increased VR realism and difficulty walking on cobbled terrain using SS rendering. Thus, results indicate that the integrated haptic system demonstrates promise in potential gait training for PD in future work.**

***Index Terms*—Haptics, terrain display, virtual reality, gait training.**

I. Introduction

VIRTUAL Reality (VR) has been proven effective for military training [1], industrial training [2], medical training [3], and gait training [4], [5] since it offers the ability to replicate immersive scenarios in a safe and controlled environment. When combined with a locomotion interface, it allows the user to explore the VR world freely thanks to the infinite workspace provided by robotic steppers [6], [7] or treadmills [8], [9]. Interventions through graphical and haptic methods can be introduced using stereo displays [10], [11] or torso forces [12], [13] to help increase realism and create challenging scenarios. However, terrain rendering with these devices are mostly restricted to graphical representations with limited haptic rendering of gross features, like stairs and slopes. Their effects on gait characteristics [10], [14] and training [10], [15] are also investigated.

Our prior work [16], [17] introduced the Smart Shoe (SS), Fig. 1 (a), for haptic terrain rendering, which was evaluated in a non-VR environment. This work integrates the SS with VR to allow physical display of terrain characteristics presented graphically in virtual worlds. According to the authors' knowledge, the SS is the first wearable device that renders both gross sloped terrain and subtle terrain, like small objects or uneven surfaces. The combination of physical and virtual terrain display allows us to create realistic and challenging walking scenarios for increased realism and perturbed gait characteristics in a treadmill-based VR system. Such a combined uneven terrain rendering system with rich graphics, enhanced haptics, and natural locomotion is new and potentially useful for gait training in future work.

The SS provides an augmented sense of the virtual terrain through altered foot-ground interactions as the user locomotes. It utilizes a multi-bladder mechatronic shoe sole that changes the way the ground feels when a user steps on it. This is done by actuating selected pneumatic valves to allow specific bladders to deflate which mimics the desired terrain under the foot. This allows passive bladder deflation by the user's body weight as he or she steps on the SS during the stance phase of gait. Bladder reinflation is also achieved passively by the rebound force of the elastomeric structure when valves are opened during the swing phase of gait. Thus, both gross terrain slopes and subtle terrain features, like stepping on an object or an uneven surface, can be rendered during each step through coordinated bladder actuation. Haptic feedback, including kinesthetic cues (i.e., foot, limb, and body pose changes by altering the bladder sole shape) and cutaneous cues (i.e., forces by varying bladder shape and internal pressure) are presented by the SS [17].

VR display and locomotion are provided by the SARCOS TreadPort locomotion interface with additional floor projection [8], Fig. 1 (b), which is based upon a treadmill featuring

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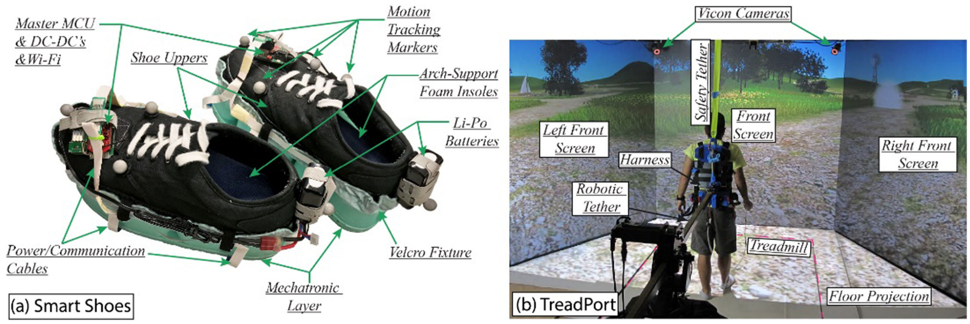

Fig. 1. (a) The soft robotic Smart Shoe; (b) The TreadPort VR locomotion system at The University of Utah.

self-selected walking speed [14]. Graphical display of the virtual world is provided by a 180°CAVE display with floor projection to provide more immersive display of the terrain. When walking in the TreadPort, the user's motion is synchronized between the treadmill and the graphical world, such that the user's forward motion drives the virtual world past the user as if they were walking in the VR world. Turning in the TreadPort is controlled by the user turning their torso in the direction that they want to walk, which causes the virtual world to yaw proportional to their torso angle relative to a robotic tether attached to the harness worn by the user [15]. Thus, terrain features projected on the treadmill belt move at the same speed as the belt, which makes it seem as though the terrain is painted on the belt in the user's view. The SS collides with the terrain graphics at heel-strike and then renders features of the graphical terrain at that location by opening appropriate valves to simulate that terrain. The SS actuates to re-inflate all bladders after gait toe-off and resets for the next foot-ground collision. The user wears a pair of SS, such that the user perceives terrain with both feet during gait.

A. Related Work

Most existing terrain rendering devices rely on large robotic devices to apply kinesthetic stimuli to render gross terrain features, including slopes, stairs, and bumpy surfaces [6]–[9], [18]. Although they can replicate those gross features effectively using simple VR graphical display, they are not able to render fine terrain features. The portability of these large robotic devices is also limited. There is portable instrumented footwear that relate to this work, but they do not provide interactions with VR, thus, lacking immersiveness. Gait Enhancing Mobile Shoe (GEMS) [19] emulates a split-belt treadmill using spiral wheels under the shoe. Re-Step [20] create programmed perturbations using linear actuators attached to the shoe. Both devices are purely intended for providing assisted gait training in the real world, which has limitations in its safety and variability. More recently, the Level-Ups [21] were developed to use motorized stilts to change vertical elevation for the sense of stepping on elevated surfaces displayed in a VR headset. The RealWalk [22] can create a variety of ground material deformation in VR, such as snow, mud, and dry sand by modulating the viscosity of the Magnetorheological fluid in the shoe sole. The fluidic haptic interface is used to render different levels of compressibility that mimics complex material properties [23].

When it comes to walking and gait training, exploration of such a VR device is very limited compared to the infinite walking experience in a treadmill-based CAVE such as presented here. Moreover, the previously mentioned devices are unable to render sub-foot-sized subtle features, and cannot provide an unencumbered VR experience, in which the user can see and interact with the VR terrain as they are stepping on it.

Treadmill based gait training has been popular and effective for training people with walking impediments such as PD [24], Spinal Cord Injury (SCI) [25], and post-stroke [26], to improve their walking capability. More recently, VR and haptic devices [4], [10], [11], [15], [27], [28] have also been incorporated to enhance human-computer interactions for improved experience during prolonged walking sessions. Various controlled interventions, mainly graphical and torso force feedback, could be applied in VR. However, haptic terrain intervention for gait training has not been reported in existing treadmill-based VR systems.

The latest SS [17] was developed based upon prior versions [16] using innovative fabric compositing techniques [29]. Comprehensive test results demonstrated significantly improved durability and appropriate terrain rendering capability for extensive PD training. Previously, our group has demonstrated stepping over 3D projected obstacles in the TreadPort [11]. In this work, the SS is integrated with the TreadPort for rendering terrain features in VR, allowing the SS to be used as a gait perturbation device for the first time. Cobblestone is rendered in the form of 2D graphical representations and haptic feedback from the SS. Both participants with PD and HE participants' gait characteristics are evaluated, providing important pilot data in the form of survey and experimental results for evaluating the SS as a potential gait training tool in future work.

B. Contributions

This work makes several contributions to further the knowledge of rendering uneven terrain using the SS in VR. The first contribution is the SS integration with the TreadPort system, including the motion tracking and the graphics systems (e.g., graphical projection and VR models running in Unity). Real-time foot tracking and terrain querying in VR are achieved and synchronized with the graphical projection. Fast SS control based upon subtle terrain height variations at the foot position in the VR model triggers bladder commands automatically to render the features. Gait phases are monitored to cycle shoe reinflation during gait swing phase and to render features during foot-ground contact. As a result, the user can feel the uneven surface when stepping onto the terrain projected on the moving treadmill belt.

Second, this work contributes pilot data from human participant tests evaluating effectiveness of the proposed system as a haptic device for physical terrain rendering. Results compare Healthy Elderly (HE) participants and participants with PD using regular shoes, Smart Shoes without rendering enabled, and Smart Shoes with Rendering enabled. Haptic interaction is measured via differences in gait characteristics and participant questionnaire results. While pilot study kinematic data suggests that the weight and compliance of the SS may introduce locomotion challenges in and of itself, pilot study survey data further suggests that SS terrain rendering further increases VR realism and makes locomotion over cobbled surfaces more challenging. Kinematics results also suggest that SS rendering induces changes in ankle kinematics and compensatory gait mechanisms. All of these features are desired for PD gait therapy where the goal would be to create realistic and controllable locomotion challenges in a safe environment. These conclusions are stated cautiously due to limited pilot study power (0.72 for spatiotemporal results, 0.65 for kinematics, and 0.78 for survey data), but the work does suggest that the SS terrain rendering could be used for PD gait rehabilitation in a VR environment. Results provide a valuable guide for designing future studies.

C. Paper Structure

The structure of this paper is described as follows. The Smart Shoe and the terrain rendering system in the TreadPort are first presented in Section II. Section III presents the test method of this pilot study. Corresponding test results are presented in Section IV with focus on gait spatiotemporal parameters (including minimum toe clearance), gait kinematics, and questionnaire responses. Discussion of results and possible future work are also provided. The paper then concludes in Section V with conclusions.

II. Terrain-Enabled VR System

The terrain-enabled VR system consists of the Smart Shoe physical terrain rendering system, a Cave Automatic Virtual Environment (CAVE) based graphical terrain rendering and locomotion system, named the TreadPort, and supporting systems to couple these systems. This section describes each of these in greater detail in the following subsections.

A. Smart Shoes for Physical Terrain Rendering

The core of the soft robotic SS [17] is the instrumented bladders in the shoe sole, Fig. 1 (a) and Fig. 2.

1) Bladder Layout: Bladder layout and shapes are customized based upon typical foot anatomy and foot pressure profile during gait. The early versions [16], i.e., versions 1 and 2, used twelve and seven bladders in forefoot, mid foot, and hind-foot segments, with the idea that more bladders would allow finer haptic display. But due to space and flexibility constraints, the seven-bladder layout demonstrated better performance and was later improved in version 3 [30]. The version 4 layout used a 2-by-4 array of round and separate composite bladders in each shoe sole for reduced stress concentrations and improved shoe stiffness [29], [30]. However, it was still not optimized due to partial loss of support from gaps between bladders.

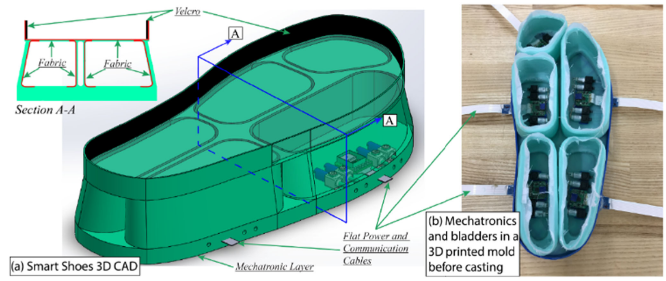

Fig. 2. (a) Smart Shoe 3D CAD and cross-sectional view highlighting SS bladder layout, embedded mechatronics, and fabric reinforcement; (b) Photo of the mechatronics and composite bladders assembled before casting liquid rubber to mold the mechatronic layer at the bottom of SS. Note the white embedded fabric in the bladders extends out and is ready to be molded into the top layer.

The current SS (version 5) bladder layout design [17] used in this pilot study, Fig. 2, consists of five separate bladders with round corners to reduce stress concentration when buckled. Gaps between bladders were minimized for improved support, while minimizing interference between adjacent bladders. Bladder shapes were further optimized through numerical simulation based parametric studies and multi-objective design optimization to achieve consistent performance among different users while balancing range of motion and stability of the SS.

2) Fabric-Rubber Composite Bladders: SS manufacturing incorporates 3D printing, liquid rubber casting, and fabric compositing techniques [29] for rapid prototyping of highly durable thin-walled pneumatic bladders with large load capacity for increased bladder stiffness, Fig. 2 (b). The fabric-rubber composite bladders in versions 4 and 5 are significantly stronger and more durable, and were tested for over 200K cycles of simulated heel strikes without suffering catastrophic failures. The targeted number of cycles is about 120K, which is sufficient for 3 users to complete their gait training sessions consisting of 45 minutes per session, 3 sessions per week for 6 weeks.

3) Mechatronics: The SS utilizes embedded mechatronics in each bladder, Figs. 2 and 3, to modulate bladder pressure and height indicated by desired terrain features. It communicates wirelessly with a control computer, usually running VR terrain querying algorithms based upon real-time motion tracking. External electronics on top of the SS upper, including a master microcontroller board with WiFi chip, DC-DC modules, and battery packs, manage both downstream control, i.e., I^2C communication and power distribution down to each bladder via flexible flat cables, and upstream data reporting to a control computer. Each embedded slave module contains a proximity sensor, a pressure sensor, pneumatic valves, and a microcontroller with transistors for valve control, Fig. 3.

4) SS Integration: The SS bladders and embedded mechatronics are combined by molding the bottom mechatronic

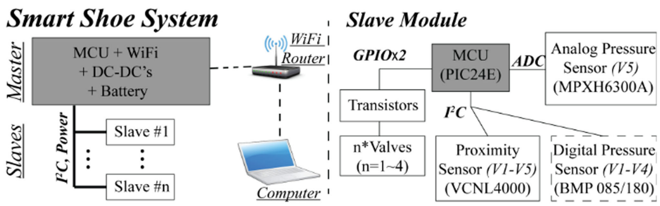

Fig. 3. Smart Shoe mechatronic system and slave module diagram.

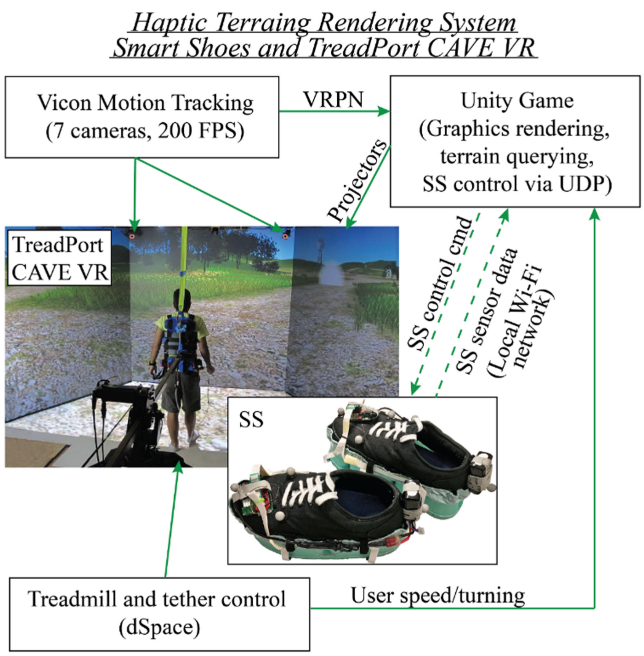

Fig. 4. Smart Shoe/TreadPort terrain rendering system diagram highlighting functionalities for each and between subsystems.

layer as one piece. The fabric reinforced bladder top layer also connects all bladders. This fabric reinforcement extends out and is stitched with Velcro for attaching a shoe upper, which is then strapped with external microcontroller boards and battery packs. Motion tracking spheres are glued on the upper for real-time shoe tracking in VR. Three pairs of SS soles, featuring small (892 grams each), medium (994 grams each), and large (1120 grams each) sizes, are customized for users requiring different shoe sizes. However, the SS is slightly heavier and softer than regular shoes due to instrumentation. Regular shoes weigh as little as 300 grams each for light running shoes, about 500 grams each for regular casual sneakers, and over 1000 grams each for boots. The increased weight of the SS could potentially affect gait.

B. *TreadPort Locomotion Interface*

The terrain rendering system in the TreadPort locomotion interface consists of four subsystems, Fig. 4, including the Unity game engine and the CAVE displays (i.e., 180-degree frontal and floor projections and screens), the treadmill and tether control system using a dSpace controller for self-selected walking speed, the Vicon motion tracking system, and the tetherless SS for haptic terrain rendering.

Fig. 5. SS test in a virtual farm when the participant walks on a 20 m long cobblestone walkway with inset figure showing the actual terrain panel [31], [32] used to generate the VR terrain. Note the motion tracking markers show as bright dots under camera flash light; also notice the yellow safety belt attached to the harness and the safety bars in front of the participant as an optional safety device when needed.

First, the graphical representations of the scene, such as buildings, plants, cobblestones, obstacles, animals, etc., are constructed in the Unity software and then projected directly onto three front screens and the wide treadmill belt, Fig. 1 (b). The remainder of the floor next to the treadmill is covered with white screen material so that the floor projection is seamlessly merged with the front screens. In this work, the uneven cobblestone surfaces are modeled by 3D scanning an off-the-shelf mock cobblestone panel [31], inset of Fig. 5. The 3D graphical model of the cobblestone panel is then duplicated in the VR scene to create cobblestone walkways for participant to walk on, Fig. 5.

Second, the SARCOS treadmill (10ft x 6ft) provides self-selected speed [14] using a six-axis robotic tether attached to the back of the safety harness [8], Fig. 1f (b). As the user steps forward, the torso movement drives the tether forward, which is then converted to the treadmill belt backward motion to move the user's feet back. Thus, the user is re-centered (in the anterior-posterior direction/forward-backward direction) on the treadmill before the next step. Kinesthetic force feedback can be applied to the user's torso using the same robotic tether in order to create a stable and energetically realistic walking experience [8]. The treadmill belt speed and torso orientation signals are sent to the Unity game to synchronize the movement and rotation of the user's view to mimic locomotion in the real world.

C. *Real-time Motion Tracking and Terrain Querying*

Third, a seven-camera Vicon Bonita motion tracking system is optimized to track the user's feet and lower body motion inside the TreadPort CAVE. The 3D motion tracking data is broadcast in real-time through a TCP based Virtual Reality Peripheral Network (VRPN) at 200 Hz. Terrain querying in the Unity game is then achieved using the real-time foot location, which is obtained from the VRPN packets at about 60 frames per second. At each frame, foot location is first determined by motion capture and sent to the Unity game. The height of the graphical representation of the virtual terrain is calculated under each SS bladder to determine whether each bladder should open or close. In this work, open loop SS control is used to display the general unevenness. Fine bladder height control or deflection rate control to simulate variable terrain impedance is the topic of future work.

Before the user's foot lands on a targeted cobblestone surface, all SS bladders keep fully inflated to simulate walking on a flat surface. When the foot is about to collide with the uneven cobblestone surface, i.e., right before heel-strike, the Unity game generates the SS control commands and sends them to the SS via UDP over WIFI to open the valves in the desired bladders to allow deflation. Thus, the user can feel high or low spots and unevenness under each foot that matches the surface seen in the graphical display. As the user lifts their foot off the ground, i.e., after toe-off, the SS then resets and allows the bladder to re-inflate passively by opening the valves. Therefore, as the treadmill and graphics systems update, terrain features can be rendered continuously by the SS with each new step. After the user's foot leaves the uneven surface and is about to collide with the flat surface again, all SS bladders reset to the fully inflated state. The transition from walking on a flat surface to an uneven cobblestone surface, and then back on a flat surface, results in different rendering, which contributes to the VR realism. This is because the SS system recognizes user foot placement in the VR world and changes the foot contact experience based upon the graphical terrain that the user is stepping on.

In this work, heel-strike is automatically detected by custom Unity code using the heel marker; when the heel marker trajectory reaches a local minimum, heel contact is assumed to have occurred. Toe-off is detected similarly when the toe marker rises above a local minimum.

III. Methods

The goal of this pilot study was to assess the performance of SS rendering with PD participants, with potential application to gait training in clinical populations for future work. HE participants were included to compare PD responses against those from a healthy/normal population which helps determine if PD participants can use this technology in future work, such as gait training in a controlled environment. The study also examined whether the SS added to the VR experience. Prior work [17] evaluated operation of the SS during a single step in a non-VR environment, whereas this work evaluates SS efficacy in continuous walking within a VR environment. Spatiotemporal gait properties and kinematics are evaluated to measure physical changes caused by the SS whereas questionnaire data is used to evaluate user perception. Participants were evaluated walking with regular shoes or with the SS in the TreadPort while exploring a virtual world. The study was completed with University of Utah IRB #00092376 approval. Details of system setup and participant experimental procedures are presented in this section.

Two safety devices, Fig. 5, are present in the TreadPort to ensure safety while not impeding walking. The first device is a safety harness with a belt connected to the building beam on the roof. It loosely hangs from the ceiling and immediately locks in case the user falls, similar to a seat belt in a car. The second safety device is a safety bar that is mounted across the treadmill in front of the user. This was meant to be an optional safety device for PD participants to hold on to when necessary, which was found to be important to prevent PD participants' gait from freezing in prior VR studies in the TreadPort [11]. The bar was also made available to HE participants for consistency.

Eleven participants participated in the pilot study: five HE participants (3 males and 2 females) with mean age and standard deviation (59.4 $\pm$ 7.2) and mean height and standard deviation (1.76 $\pm$ 0.09 m) and six PD participants (3 males 3 females) with mean age and standard deviation (67.8 $\pm$ 5.9) and mean height and standard deviation (1.74 $\pm$ 0.11 m). All PD participants were screened by a set of pre-tests before using the TreadPort to assure that disease progression did not limit their ability to participate. Inclusion was based upon medically confirmed diagnosis of mild to moderate idiopathic PD (Hoehn and Yahr Stage II –III), >40 years of age, currently taking dopamine replacement medication, normal general sensation in the lower extremities, gait related balance impairments, and hypokinetic gait. The pre-tests included a 6-minute walking test [33], a 10 m walking test, and a Movement Disorder Society-sponsored revision of the Unified Parkinson's Disease Rating Scale (MDS-UPDRS) test [34].

None of the HE participants and three of the six PD participants had ever used the TreadPort before. None had used the SS before. All participants underwent a $\sim$3 to $\sim$5-minute walking training until they were comfortable using the TreadPort and SS. Participants were first instrumented with the Modified Plug-In-Gait (Vicon) marker set defining 7 segments (pelvis, thighs, shanks, and feet) using 41 markers captured at 200 Hz, Fig. 6. A harness was then donned by the participant, which provided fall arrest protection as well as control of the TreadPort.

A virtual farm was used for the participant studies, Fig. 5. Numerous paths in the farm are "paved" with cobblestone panels ($\sim$20 m long) modeled after those used in [31], [32]. Participants were asked to walk along the path with a comfortable walking speed while wearing their regular walking shoes and the SS. Three test sessions were conducted, including walking with regular shoes (Reg), fully inflated SS (SS-I), and SS with terrain rendering enabled (SS-R). Three pairs of SS, small, medium, and large, were used to fit participants with different foot sizes. The SS only renders uneven cobblestone surfaces when the participant steps onto the cobblestone during the SS-R trials. Randomized shoe order was used for each participant. However, to minimize how often the participants changed their shoes during the test, the SS trials were grouped together, which resulted in testing with regular shoes first or last.

Three trials with a minimum of ten steps per foot after reaching steady state was captured by the motion capture system when the participant walked on the VR cobblestone walkway. Irregular gait caused by turning in VR was minimized by only recording steps when participants walked in a straight

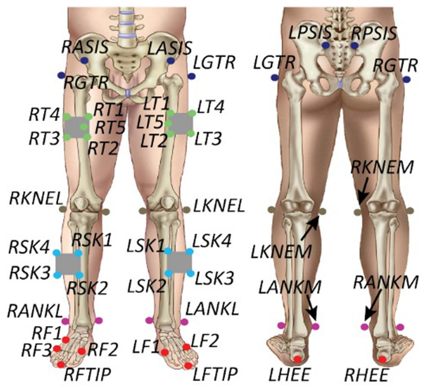

Fig. 6. Modified Plug-In-Gait (Vicon) marker set defining seven segments, including pelvis, thighs, shanks, and feet, using 41 markers.

line. Motion tracking data was then post-processed in Nexus (Vicon) and Visual 3D (C-Motion).

Kinesthetic aspects of the haptic responses were evaluated with spatiotemporal gait properties and kinematics derived from motion capture data to evaluate the change in gait characteristics associated with walking with the different shoe configurations. This allows measurement of kinesthetic haptic response (e.g., changes in motion) since direct cutaneous measurement of foot forces is not possible due to challenges instrumenting the foot inside the SS, previously discussed in [17]. Participant questionnaire scores evaluating SS properties, SS performance in VR, and its effect on gait were also collected.

To understand the effects of subject type and shoe configuration on spatiotemporal gait properties and kinematics, we employed a two-way ANOVA with repeated measures: two levels of subject type and three levels of shoe configurations with repeated measures on the shoe configuration. The subject type was either HE or PD while shoe configuration was either Reg, SS-I, or SS-R. Post hoc comparison with Bonferroni correction was used to identify statistical significance between multiple cases. We used a significance level of $\alpha = 0.05$. Bonferroni correction was applied to the p value instead of α such that F and t statistics could be reported without confusion. Likewise, there were three comparisons needed to evaluate differences between shoe configuration which include SS-R/Reg, SS-I/Reg, and SS-R/SS-I; thus, p values were scaled up by a factor of three instead of scaling alpha.

IV. Experimental Results

Results are presented in three sections: gait spatiotemporal parameters, gait kinematic parameters, and questionnaire results. Results of the ANOVAs are presented in tables and show mean, standard deviation, and relevant statistics. Plots of subject data and confidence intervals accompany each table. We hypothesized that there would be changes in spatiotemporal and kinematic gait variables between groups. We also hypothesized that within each group for the different shoe conditions, we would see changes in spatiotemporal and kinematic variables. Lastly, we hypothesized that both groups would subjectively rate a higher VR experience using the SS-R vs SS-I or Reg.

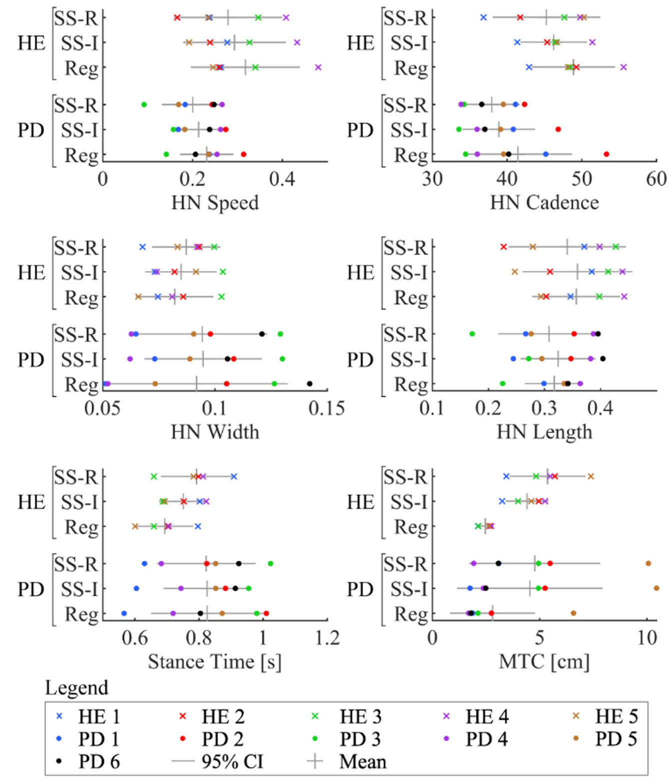

Fig. 7. Spatiotemporal gait parameters presented as 95% confidence intervals with subject responses indicated by color and shape.

A. Gait Spatiotemporal Parameters

Gait spatiotemporal parameters, Fig. 7 and Table I, including speed, cadence, step length, step width, and stance time are derived from foot trajectories, Fig. 8. Speed, cadence step length and step width are Height Normalized (HN) for each participant based on [14]. Results of the ANOVA reveal that subject type had a statistically significant effect on HN Speed ($F(1, 32) = 9.15$, $p = .005$) and HN Cadence ($F(1, 32) = 17.69$, $p < .001$). Further t-test analysis reveals that PD participants were on average 0.08 slower, or about 27% overall, than HE participants ($t(27) = 3.02$, $p = .005$). Similarly, PD participants had a significantly slower HN Cadence by an average of 11.0 ($t(27) = 4.20$, $p = .005$). These results are expected because PD participants tend to have a slower gait than HE participants [35], which has also been demonstrated on real cobbled surfaces use to generate the VR simulations here [32].

Shoe configuration had a statistically significant effect on MTC ($F(2, 32) = 3.84$. $p = .034$). Results of the t-test indicate that participants wearing SS-R increased their toe clearance by 2.39 cm when compared to Reg ($t(27) = 2.66$, $p = .039$). However, SS-I was not statistically different from Reg ($t(27) = 2.01$, $p = .49$) nor SS-R ($t(27) = 0.64$, $p = .99$). MTC results, Fig. 7, suggest a possible distinction in MTC for HE and PD participants wearing SS-I or SS-R vs reg, but ANOVA analysis indicates that there is not a statistically significant distinction. This could be explained in part by the large variation in PD MTC noted in Fig. 7 and low number of PD participants.

TABLE I
ANOVA Results for Spatiotemporal Parameters. Results Are Height-Normalized (HN) With Respect to Each Participant's Height

Spatiotemporal Parameters		HN Speed	HN Cadence	HN Width	HN Length	Stance Time [s]	MTC [cm]
Average ± 1 std	HE SS-R	0.279 ± 0.097	45.2 ± 5.8	0.08 ± 0.01	0.34 ± 0.08	0.79 ± 0.09	5.37 ± 1.43
	HE SS-I	0.294 ± 0.092	46.2 ± 3.6	0.08 ± 0.01	0.36 ± 0.08	0.75 ± 0.06	4.41 ± 0.80
	HE Reg	0.318 ± 0.098	48.9 ± 4.5	0.09 ± 0.01	0.36 ± 0.06	0.69 ± 0.07	2.46 ± 0.31
	PD SS-R	0.200 ± 0.066	37.9 ± 3.6	0.09 ± 0.03	0.31 ± 0.08	0.82 ± 0.15	4.76 ± 2.91
	PD SS-I	0.214 ± 0.051	38.9 ± 4.6	0.09 ± 0.03	0.32 ± 0.06	0.83 ± 0.17	4.54 ± 3.23
	PD Reg	0.231 ± 0.057	41.4 ± 6.9	0.08 ± 0.03	0.31 ± 0.05	0.83 ± 0.17	2.80 ± 1.89
Subject: F(1,32)		9.15	17.69	1.07	1.99	3.44	0.001
Shoe: F(2,32)		0.57	1.48	0.07	0.17	0.44	3.84
Subject*Shoe: F(2,32)		0.01	0.001	0.01	0.01	0.49	0.15
Subject: p		.005*	< .001*	.310	.170	.075	.952
Shoe: p		.570	.246	.932	.848	.650	.034*
Subject*Shoe: p		.992	.999	.990	.993	.620	.865

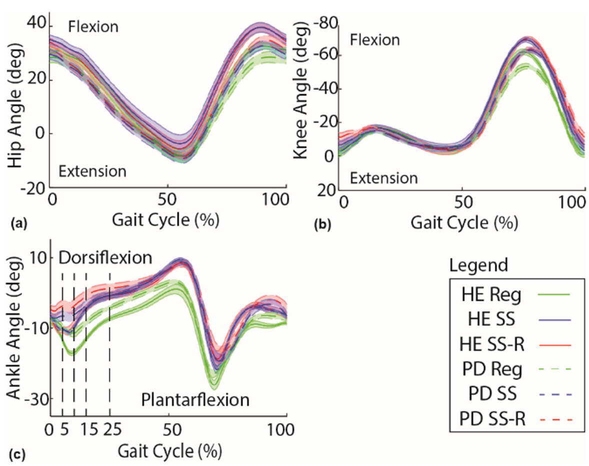

Fig. 8. Gait kinematics of participants showing mean and standard errors.

Participant PD5, for example, demonstrated much larger MTC with notable variation between SS and REG, whereas participant PD1 had a very small MTC and very little difference in MTC between shoe configurations.

Minimum Toe Clearance (MTC) is the most important gait metric associated with the highest risk of unintentional ground contact (e.g., tripping) [36], leading to potential falls. Existing literature reports increased MTC when walking on irregular floor surfaces [37] and while wearing heavier footwear to avoid tripping when stepping over obstacles [38]. Given [37], the above ANOVA and t-test results suggest that increased MTC may be due to the uneven terrain rendering provided by the SS-R, although the variation in MTC noted in the HE population could suggest that it is related to shoe weight and lifting the foot higher to counter potential tripping while stepping over the virtual obstacles [38].

Power analysis on the comparisons for spatiotemporal gait properties reveal an average power of 0.72. Further analysis indicates that approximately 6 additional participants are needed within both the HE and PD groups to raise the power to 0.8, which is helpful for designing future studies related to SS.

B. *Gait Kinematic Parameters*

Gait kinematic parameters, including hip angle, knee angle, and ankle angle in the sagittal plane are important measures of how people walk. In this work, kinematic angles are normalized for each step from heel-strike to the subsequent heel-strike on the same foot, or 0% to 100% gait cycle, within groups of HE participants and participants with PD, Fig. 8.

Two-way ANOVA was performed on the maximum and minimum angles of hip, knee, and ankle, as well as the range of motion for each respective joint, Table II and Fig. 9. Results reveal that subject type had a statistically significant effect on maximum knee angle ($F(1, 27) = 5.67$, $p = .025$). Further t-tests reveal that PD patients compared to HE had reduced maximum knee angle of 6.5° ($t(27) = 2.38$, $p = .024$). This is likely caused by typical PD shuffle gait [35].

Shoe configuration had statistically significant effects on minimum knee angle ($F(2, 27) = 5.07$, $p = .014$) and maximum ankle angle ($F(2, 27) = 7.79$, $p = .002$). Participants that walked with SS-R showed minimum knee angle reduced by 16.9° compared to Reg ($t(27) = 2.88$, $p = .023$) and a 16.0° reduction for SS-I compared to Reg ($t(27) = 2.61$, $p = .043$). Both HE and PD also show statistically significant increases in maximum ankle angle (dorsiflexion) during the swing phase; SS-R increased by an average of 6.5° compared to Reg ($t(27) = 3.29$, $p = .008$); SS-I increased by 7.0° compared to Reg ($t(27) = 3.53$, $p = .005$). These increases in knee flexion and ankle dorsiflexion are likely the direct cause of the increased MTC [39] noted in the last section attributed to walking over irregular surfaces [37]. They could be related to terrain rendering since they were only significant in the SS-R vs Reg, but they could also be related to compensatory mechanisms [39, [40] caused by the increased weight of the SS system since they were present in both SS-R and SS-I here. Further investigation with a well-powered study is warranted.

The SS uneven surface rendering effect can be investigated by evaluating the differences between different shoe configurations and subject type during the stance phase, which can be divided into three rockers [41], i.e., heel rocker, ankle rocker,

TABLE II
ANOVA RESULTS FOR KINEMATIC PARAMETERS

Kinematic Parameters		Hip [deg]			Knee [deg]			Ankle [deg]		
		Min	Max	ROM	Min	Max	ROM	Min	Max	ROM
Average ± 1 std	HE SS-R	-4.8 ± 10.8	39.3 ± 7.9	46.5 ± 8.9	-67.6 ± 6.0	-2.8 ± 8.3	70.3 ± 8.0	-24.9 ± 11.9	10.2 ± 2.7	31.8 ± 6.6
	HE SS-I	-1.8 ± 10.7	39.4 ± 7.7	44.2 ± 7.6	-68.3 ± 6.9	-2.2 ± 8.9	69.4 ± 5.5	-25.9 ± 8.8	11.1 ± 1.4	33.7 ± 5.5
	HE Reg	-4.0 ± 5.4	34.0 ± 8.1	42.4 ± 8.3	-62.8 ± 7.1	-2.0 ± 8.4	64.1 ± 4.8	-27.5 ± 6.5	4.4 ± 2.4	30.3 ± 5.2
	PD SS-R	-10.1 ± 11.9	36.4 ± 10.9	44.6 ± 2.5	-69.0 ± 7.8	2.3 ± 8.0	66.7 ± 8.6	-21.7 ± 7.0	9.2 ± 5.8	33.6 ± 8.7
	PD SS-I	-11.8 ± 13.7	34.7 ± 11.3	44.0 ± 6.5	-66.7 ± 7.4	3.8 ± 7.9	67.7 ± 9.9	-24.1 ± 3.5	9.1 ± 5.5	36.1 ± 6.6
	PD Reg	-13.0 ± 14.1	29.9 ± 10.5	39.3 ± 5.6	-55.9 ± 7.8	6.6 ± 5.7	59.7 ± 7.1	-29.2 ± 3.8	1.9 ± 6.3	32.5 ± 4.7
Subject: F(1,32)		3.92	1.34	0.55	0.87	5.67	1.47	0.19	1.35	0.87
Shoe: F(2,32)		0.06	1.18	1.40	5.07	0.29	2.72	1.38	7.79	0.83
Subject*Shoe: F(2,32)		0.12	0.03	0.12	0.94	0.14	0.09	0.34	0.08	0.001
Subject: p		.058	.258	.463	.358	.025*	.236	.664	.255	.360
Shoe: p		.944	.323	.263	.014*	.749	.084	.269	.002*	.448
Subject*Shoe: p		.886	.974	.883	.403	.870	.917	.712	.922	.995

and forefoot rocker. Ideally, the uneven rendering is expected to cause gait perturbations during all three rockers, but only the first two rockers show statistical significance.

Two-way ANOVA was performed on ankle angle during the four different stages of the gait, Fig. 8, through the heel rocker and the ankle rocker (i.e., 5%, 10%, 15% (about foot-flat) and 25% (about mid-stance)), Fig. 10. These four stages were selected since they indicate the initial SS deflation process to the full deflation at about mid-stance.

Results, Table III and Fig. 11, indicate that subject type had a statistically significant effect on ankle angle at 5% gait cycle ($F(1, 32) = 4.26$, $p = .049$). T-tests indicate that PD participants held a statistically significant higher ankle angle on average when compared to HE ($t(27) = 2.06$, $p = .049$); PD participants held an average ankle angle of 83.4° while HE participants held an average ankle angle of 78.9°. This was expected as people with PD tend to have reduced ankle flexion with shuffle gait [35].

ANOVA indicates that at 10% gait cycle shoe type is potentially of significance ($F(2, 32) = 3.34$, $p = .051$); further inspection shows there is a notable 7.7° average increase in ankle angle with participants who wore SS-R compared to Reg, but t-tests refute the statistical significance of this result ($t(27) = 2.46$, $p = .06$).

Shoe configuration had a statistically significant effect on ankle angle at 15% gait cycle ($F(1, 32) = 4.65$, $p = .018$) and 25% gait cycle ($F(1, 32) = 3.94$, $p = .031$). At 15% gait cycle, participants who used SS-R increased their ankle angle relative to Reg by 8.1° ($t(27) = 2.87$, $p = .024$) and by 6.1° for 25% gait cycle ($t(27) = 2.60$, $p = .044$). There was no statistical significance between Reg and SS-I for 15% and 25% gait cycle, which suggests that rendering provided by SS-R was important.

The post-hoc power for kinematics is on average 0.65. Power analysis indicates an that an additional 14 HE and 14 PD participants are needed to raise the study's power to 0.8. Lower power in kinematics is likely due to low sample size, limitations in foot measurements due to marker placement on the shoe upper and not the foot, and natural variations due to terrain rendering based upon where the user steps on the terrain.

C. Questionnaire

A questionnaire, developed based on [43], was administered immediately after each session to collect subjective participant feedback data before progressing with the next shoe configuration. The participant was asked to answer eight questions (i.e., Q1 through Q8) regarding their VR and shoe experiences, Fig. 12.

Results of the ANOVA, Table IV, show that shoe configuration had a significant effect on Q2 "Realism of walking on Cobblestone" ($F(2, 32) = 8.91$, $p = .001$). When using the SS-R, participants reported a significant 3.78 point increase in realism when walking on cobblestone compared to Reg ($t(27) = 4.14$, $p < .001$). Similarly, SS-R was reported to be on average 2.52 points more realistic than SS-I ($t(27) = 2.76$, $p = .031$). This suggests that shoe compliance (i.e., SS-I) was a factor for increased realism on cobblestone, but SS-R rendering played an even bigger role.

Shoe configuration was also statistically significant in Q3 "Walking Difficulty" ($F(2, 32) = 8.62$, $p = .001$). There was a significant 3.53 point increase in walking difficulty, when comparing SS-R to Reg ($t(27) = 3.61$, $p = .004$) and a 3.51 point increase when comparing SS-I to Reg ($t(27) = 3.58$, $p = .004$). As expected, walking with the SS (SS-I and SS-R) is reported to be more difficult than with Reg, which could be related to shoe weight and compliance.

Shoe configuration was also statistically significant in Q4 "Walking Difficulty on Cobblestone" ($F(2, 32) = 8.19$, $p = .002$). SS-R was 3.84 points more difficult compared to Reg ($t(27) = 4.04$, $p = .001$). There was no statistically significant difference in difficulty between SS-I and Reg ($t(27) = 1.86$, $p = .22$) nor SS-R and SS-I ($t(27) = 2.18$, $p = .114$). These results suggest that walking with the SS-R on cobblestone in notably more challenging than with SS-I or Reg.

Shoe configuration significantly affected subject response to Q5, perceived "Shoe Stability" ($F(2, 32) = 14.11$ $p < .001$). Shoe stability decreased for SS-I and SS-R when compared to Reg. Participants reported a statistically significant decrease in stability of 3.99 points when comparing SS-I to Reg ($t(27)$

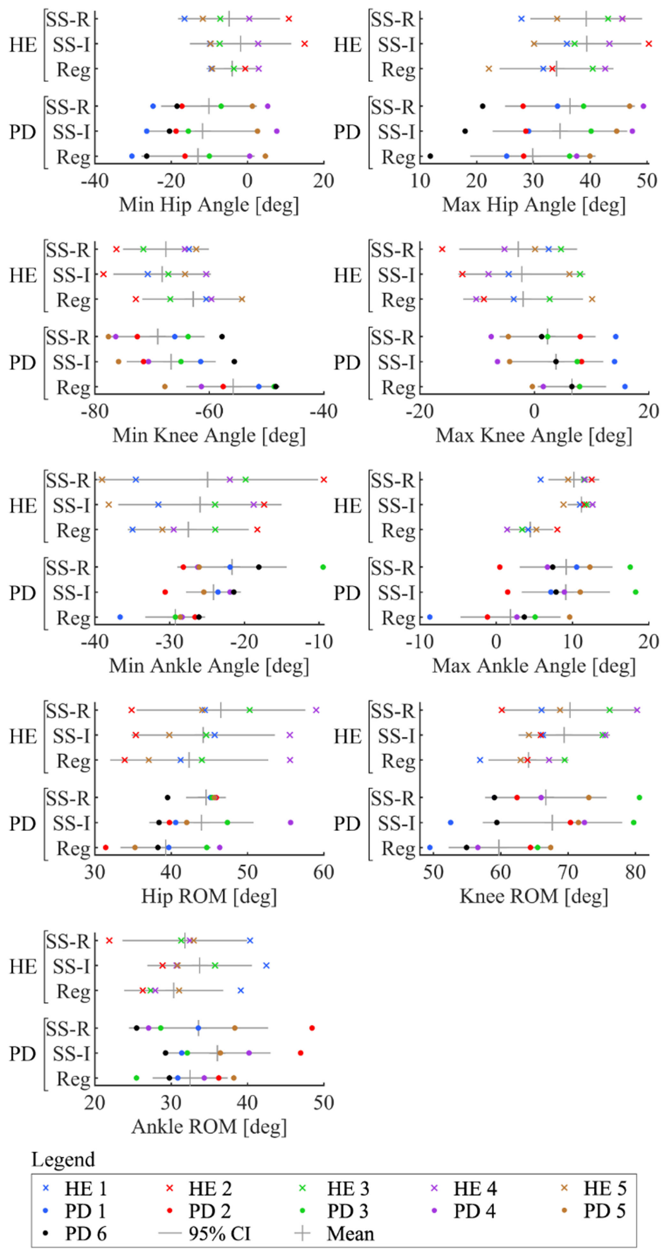

Fig. 9. Kinematic gait parameters. Results are presented as 95% confidence intervals with specific subject responses indicated by color and shape. Repeated responses are shifted upwards to differentiate participants.

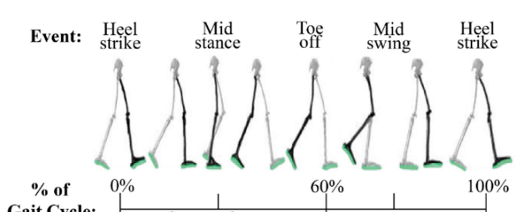

Fig. 10. Gait cycle (modified from a gait cycle figure in [42]).

TABLE III
ANOVA TEST RESULTS ON ANKLE ANGLE AT DIFFERENT STAGES OF THE GAIT FOR PARTICIPANTS WHO ARE HE AND PARTICIPANTS WITH PD

Ankle Angle [deg]		Gait Cycle			
		5%	10%	15%	25%
Average Ankle Angle ± 1 std	HE SS-R	-10.5 ± 3.8	-9.4 ± 6.1	-4.8 ± 5.3	-0.9 ± 4.6
	HE SS-I	-10.2 ± 1.9	-10.2 ± 3.2	-5.1 ± 3.2	-0.8 ± 3.6
	HE Reg	-12.6 ± 2.8	-17.1 ± 3.1	-13.5 ± 2.9	-7.5 ± 2.6
	PD SS-R	-3.8 ± 9.6	-3.9 ± 11.0	-1.1 ± 9.7	1.2 ± 7.8
	PD SS-I	-6.7 ± 8.0	-6.4 ± 8.8	-3.8 ± 8.7	-0.8 ± 6.9
	PD Reg	-9.4 ± 5.3	-11.4 ± 6.3	-8.7 ± 5.8	-4.3 ± 4.2
Subject: F(1,32)		4.26	3.92	1.92	0.84
Shoe: F(2,32)		1.11	3.34	4.65	3.94
Subject*Shoe: F(2,32)		0.27	0.06	0.19	0.24
Subject: p		.049*	.058	.177	.368
Shoe: p		.343	.051	.018*	.031*
Subject*Shoe: p		.766	.946	.826	.791

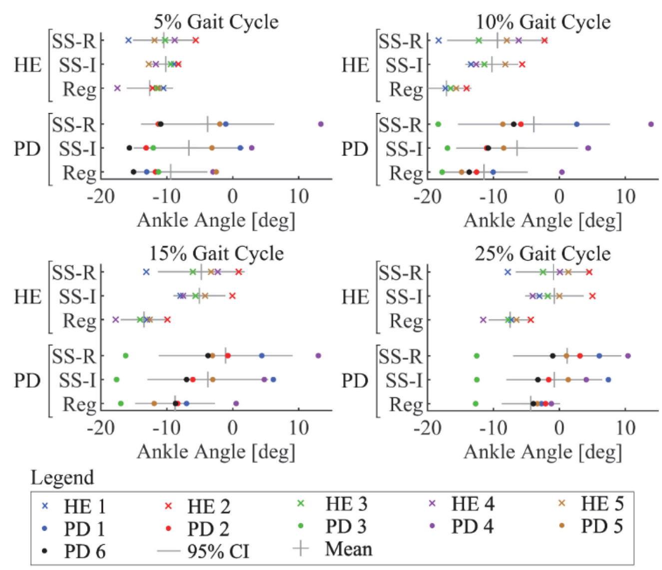

Fig. 11 Ankle Angle [deg] at various points in the gait cycle. Results are presented as 95% confidence intervals with specific subject responses indicated by color and shape. Repeated responses are shifted upwards to differentiate participants.

$= 4.76$, $p < .001$) and a decrease in stability 3.88 points when comparing SS-R to Reg ($t(27) = 4.63$, $p < .001$), which is attributed to shoe compliance. These scores are essentially neutral; scores are near 5, indicating mild instability but not uncomfortable. Stability for the SS-I and the SS-R are not statistically different ($t(27) = 0.13$, $p = .99$). Likewise, participants indicated that the "Likelihood of ankle roll over", Q6, was low, but there were no statistically significant differences between shoe type ($F(2, 27) = 2.12$, $p = .14$) or user group ($F(1, 27) = 1.96$, $p = .17$).

Participant "Fear of Walking" Q7 was affected by shoe configuration ($F(1, 32) = 5.66$, $p = .025$) and subject type ($F(2, 32) = 7.65$, $p = .002$). SS-R had an average 2.43 point increase in fear compared to Reg ($t(27) = 3.15$, $p = .012$). SS-I had a 2.76 point increase in fear relative to Reg ($t(27) = 3.58$, $p = .004$). There was no significant difference in fear between SS-R and SS-I ($t(27) = 0.43$, $p = .99$). PD participants reported an average of 1.50 points less "Fear of Walking" than HE ($t(27) =$

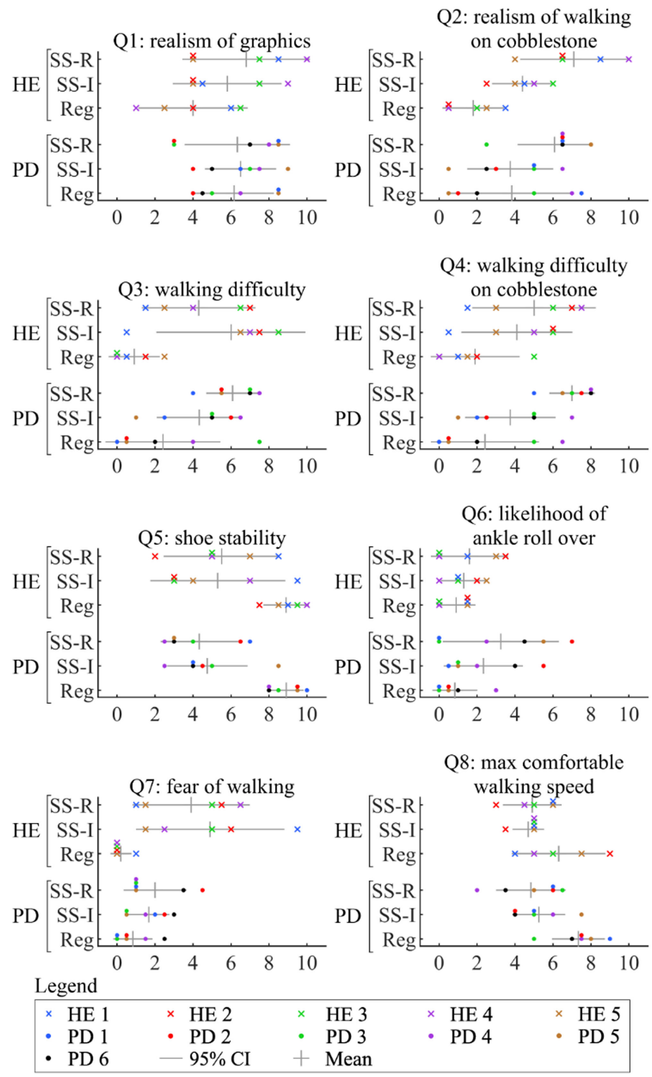

Fig. 12. SS questionnaire scores (range: 0 [low] ∼ 10 [high]) evaluating VR realism and walking performance with regular shoes (Reg), fully inflated SS (SS-I), and SS with terrain rendering (SS-R). Results are presented as 95% confidence intervals with specific subject responses indicated by color and shape. Repeated responses are shifted upwards to differentiate participants.

2.38, $p = .025$). Using the SS correlated to increased fear, but interestingly PD participants reported less fear overall. Fear of walking in the SS was actually quite low for PD participants (i.e., avg fear of 1.67 and 2.00 for SS-I and SS-R, respectively, which is near "No fear" on the Likert scale) and moderate for HE (i.e., 4.90 and 3.90 for SS-I and SS-R). We had expected PD to be more fearful, but PD participants reported that they were accustomed to overcoming walking difficulty, whereas HE participants reported that they were more uneasy by the new experience. Fear could be also correlated to shoe stability, Q5, though further study is needed.

Shoe configuration affected participant response to Q8, "Maximum Comfortable Walking Speed, ($F(2, 32) = 5.40$, $p = .012$). The maximum comfortable walking speed was reported to be an average of 1.95 points lower for SS-R compared to Reg ($t(27) = 3.13$, $p = .012$) and 1.80 points lower for SS-I compared to Reg ($t(27) = 2.96$, $p = .018$). These results agree with mean gait speed in Table I discussed in the previous subsection, which indicated that variations in gait speed were attributed to subject type. We expected that increased fear and difficulty would result in reduced walking speed and cadence in the SS-R; however, PD participants reported that they were less afraid of walking than HE participants. While spatiotemporal speed and cadence results did not provide statistically significant variation due to shoe type, the perception results presented here do indicate an impact of shoe type on user perception.

The average power for questionnaire results is 0.78, which is slightly better than the power of the spatiotemporal results (e.g., 0.72) and kinematic results (e.g., 0.65). An additional 4 HE and 4 PD participants are needed to increase the power to 0.8. Similar power was expected between questionnaire data and gait measurements. Variation in kinematic data caused low power in kinematic parameter comparisons.

D. Discussion

Our first hypothesis was that there would be changes in spatiotemporal and kinematic gait variables between groups. We found that there were significant differences in subject type for HN speed, HN cadence, maximum knee angle, and ankle angle at 5% gait cycle. Secondly, we hypothesized that within each group for the different shoe configurations, we would see changes in spatiotemporal and kinematic variables. There were significant differences correlated to shoe configuration, specifically the SS-R, for MTC, minimum knee angle, max ankle angle, and ankle angle at 15% and 25% gait cycle. These are expected with gait changes associated with walking on irregular surfaces. Lastly, we hypothesized that both groups would subjectively rate a higher VR experience using the SS-R vs SS-I or Reg. According to the questionnaire, SS-R was rated as the most realistic followed by SS-I and Reg. Users also reported significantly increased difficulty walking on cobblestone with the SS-R, which is a goal for making the terrain enabled VR experience more realistic.

While shoe type does not have a statistically significant effect on speed or cadence in this study, Xu et. al. [32] found significance ($p<0.05$) for participants (HE and PD) walking on flat ground compared to real cobblestone. The rendered cobblestone in this study was based on the real cobblestone structure of [32]. The speed and cadence values from Xu et. al. are similar to those reported here when normalized with respect to subject height [14]. Two tailed t-tests were used to test for statistical significance of height normalized speed and cadence between this study and those reported in [32], where the cobblestone surface [32] was compared to SS-R and the Flat surface [32] was compared to Reg, Table V. With the exception of HE cadence ($t(12) = 2.61$, $p = .023$) where Reg was 5.9 larger than Flat, the results suggest that there are no statistically significant differences between the results in this paper and those derived from [32]. This suggests that participants using the proposed terrain rendering system selected similar normalized speed and cadence as HE and PD participants on actual cobble, which is a good indicator of the realism created by the proposed system.

TABLE IV
ANOVA Test Results for the Questionnaire

Questionnaire		Question Number 1	2	3	4	5	6	7	8
Average ± 1 std	HE SS-R	6.80 ± 2.71	7.10 ± 2.27	4.30 ± 2.41	5.00 ± 2.62	4.50 ± 2.45	1.60 ± 1.64	3.90 ± 2.48	5.10 ± 1.24
	HE SS-I	5.80 ± 2.31	4.40 ± 1.29	6.00 ± 3.16	4.10 ± 2.36	5.30 ± 2.86	1.30 ± 0.97	4.90 ± 3.15	4.70 ± 0.67
	HE Reg	4.00 ± 2.32	1.80 ± 1.30	0.90 ± 1.08	1.90 ± 1.88	8.90 ± 0.96	0.90 ± 0.82	0.20 ± 0.45	6.30 ± 1.99
	PD SS-R	6.33 ± 2.64	6.08 ± 1.86	6.08 ± 1.32	7.00 ± 1.14	5.67 ± 1.94	3.25 ± 2.91	2.00 ± 1.58	5.17 ± 1.75
	PD SS-I	6.50 ± 1.79	3.75 ± 2.16	4.33 ± 2.14	3.75 ± 2.27	4.75 ± 2.02	2.33 ± 1.99	1.67 ± 1.03	5.25 ± 1.33
	PD Reg	6.17 ± 1.99	3.83 ± 3.08	2.42 ± 2.89	2.42 ± 2.71	8.92 ± 0.86	0.83 ± 1.13	0.83 ± 0.98	7.33 ± 1.33
Subject: F(1,32)		8.62	0.03	0.46	0.87	0.10	1.96	5.66	1.18
Shoe: F(2,32)		1.21	8.91	8.62	8.19	14.11	2.12	7.65	5.40
Subject*Shoe: F(2,32)		0.90	1.67	1.92	0.78	0.54	0.65	3.23	0.30
Subject: p		.329	.871	.502	.360	.760	.173	.025*	.288
Shoe: p		.315	.001*	.001*	.002*	<.001*	.140	.002*	.012*
Subject*Shoe: p		.419	.207	.166	.468	.586	.530	.055	.741

TABLE V
T-test Comparisons Between Height Normalized Speed and Cadence Results of Reg and SS-R in Study and Compared to Flat and Cobble in [32]

Result Comparison				HN Speed	HN Cadence
Reg/Flat	HE	Average ± 1 std	Reg	0.318 ± 0.098	48.9 ± 4.5
			Flat	0.295 ± 0.079	43.0 ± 3.8
		t-test	t(12)	0.45	2.61
			p	.661	0.023*
	PD	Average ± 1 std	Reg	0.237 ± 0.062	41.4 ± 6.9
			Flat	0.216 ± 0.110	38.4 ± 5.8
		t-test	t(13)	0.47	0.91
			p	.645	.380
SS-R/ Cobblestone	HE	Average ± 1 std	SS-R	0.279 ± 0.097	45.2 ± 5.8
			Cobble	0.270 ± 0.074	41.9 ± 4.1
		t-test	t(12)	0.17	1.22
			p	.940	.246
	PD	Average ± 1 std	SS-R	0.191 ± 0.068	37.9 ± 3.6
			Cobble	0.191 ± 0.139	35.8 ± 9.7
		t-test	t(13)	0.004	0.60
			p	.997	.559

All of these results suggest that SS-R terrain rendering coupled with the VR system provided enhanced VR experiences typified by objective measures of gait variations that support subjective questionnaire results. The aforementioned increases in realism could be leveraged in PD subject rehabilitation. The goal of such rehabilitation would be to provide challenges that increase ankle dorsiflexion during heel rocker and MTC, which are related to gait compensatory mechanisms that are important for participants to regain desired balance and motor functions, especially among the PD population. According to the authors' knowledge, this is the first work that presents a haptic terrain rendering system coupled with VR capable of providing a challenge for walking on uneven terrain in a controlled environment that is supported by objective gait analysis.

Several compromises were necessary to conduct this study, which impacted terrain rendering and foot measurements as described below. First, the SS replicates uneven cobblestone surfaces by opening selected bladders to mimic low spots and leaving others closed to mimic high spots indicated by the virtual cobblestone in VR. This results in uneven support under each foot generated by the five bladders in each shoe. This rendering scheme was originally designed for PD gait training in VR and is evaluated in this pilot study. Such unevenness primarily changes the force distribution under the foot to let the user feel the virtual terrain. However, the forces from the inflated bladders could not create large moments required to cause great ankle movement since moments on either side of the shoe cancel each other out, reducing the total moment. For example, diagonal bladders could be inflated to render cobbled stones under these parts of the foot, but since they are on the left/right side of the foot, they create forces and moments that cancel and prevent ankle motion. Hence, substantial ankle movements, like inversion, eversion, dorsiflexion, and plantar flexion demonstrated in [17], could not be replicated through cobblestone rendering. Small gait perturbations caused by the SS rendering cobblestone could still be created, which is demonstrated in this paper.

The second compromise of this work is the usage of the complete shoe upper that allowed more stable user experience but impeded more precise foot measurement. When the SS sole deforms to render terrain, more space is created inside the shoe upper to allow foot movement, but tracking markers were attached to shoe the upper. As a result, the ability to track foot motion precisely during ankle rocker and forefoot rocker was reduced, but ranges of motion were large to help offset that effect. A sandal configuration of the SS was used for participant studies in [17] with healthy young participants. It allowed more precise foot tracking since markers can be placed on the foot directly, but sandal straps did not support the foot well when the bladders deflated, causing occasionally foot slip inside sandal straps that could lead to instability. Hence, the canvas shoe upper was used in this pilot study to improve stability for participants with PD. Such an issue was deemed to be minor given the reduced ankle motion due to general terrain rendering and the fact that general gait measurements and user survey data provided sufficient evidence of the efficacy of the SS system.

Third, a safety bar was mounted across the treadmill in front of the user for them to grab onto when needed. It is an important safety device to help participants with more extreme PD or spinal cord injury symptoms having difficulty walking [10], [15]. However, such increased stability provided by the safety bar reduces measured instability in gait kinematics and spatiotemporal parameters and is considered a third potential compromise in this study. No data was recorded about how many times or how long the participants had held onto the bar. Future work should take such measurements into account, which could serve as a measure of therapy progression.

Finally, as a pilot study proven to be under powered in post-hoc analysis, conclusions need to be made with caution. Survey results showed the best power (0.78), whereas objective measures of spatiotemporal properties and kinematics are more limited, 0.72 and 0.65, respectively. In all cases, there is a probability of reaching false conclusions due to insufficient power caused by low sample sizes [44] despite low p-values in many results [45]. This work serves as a guide for designing future studies related to terrain rendering with the SS.

E. Future Work

The compromises mentioned above were important for this pilot study in order to replicate realistic terrain features, provide necessary support for improved user experience, and provide safety. It is important that future work address these compromises to improve gait perturbation and its measurement. Future work could include sloped terrain to display inversion, eversion, flexion, and dorsiflexion during gait. This would involve the addition of VR models with sloped surfaces to the virtual world. Terrain with side slopes, inclined slopes, and declining slopes, such as a trail in the mountains, could allow this. Interaction of such terrain with simulated gravity forces created by horizontal [12] and lateral [28] tethers would create a high fidelity simulation of such terrain that warrants further study.

In future work, improved measurement of foot movement inside the shoe upper should be considered. It is important to provide good foot support for safety, but new measurement techniques should be implemented to measure foot motion more precisely. A marker plate directly attached to the foot and protruding through the shoe should be able to provide this capability. Likewise, an elastic shoe upper with the capability to deform with the foot may also be considered, although it may be too tight.

The safety bar also needs to be considered in future work. PD users have demonstrated positive outcomes using the safety bar in prior VR therapy sessions [11]; thus its role in gait therapy needs to be examined. While the safety bar provides support and builds PD user confidence, it limits the effect of perturbations applied to the user. Ideally, the safety bar would be reconfigurable so a therapist or user could easily change the level of support to adapt therapy difficulty, or just remove it when desired.

Since this paper suggests that the SS is usable by PD participants, future work could also focus on applying the SS for PD gait training to evaluate its long-term training effects. This pilot study includes power analysis that specifies the number of participants needed to provide adequate power for evaluating objective and subjective measures of the proposed system, which can help design future gait training therapies. SS based therapy would be focused on outcomes that are expected to be similar to those of our prior work [10], [11], which should also be considered when designing future studies. Normality of the data should be verified to assure applicability of the ANOVA and t-test tools.

Design and control of the SS could also be revisited. A lighter and stiffer SS may reduce the effects of shoe weight and compliance observed in this study. The goal would be to create a shoe sole for improved ergonomics, more akin to the normal shoes people wear in daily life. Lighter shoe materials could be examined, but flexibility, durability, and strength are critical. Revised bladder designs could also be considered to improve stiffness. A wider variety of shoe sizes should also be provided in future studies.

The SS is designed to be used either in a VR system (CAVE or HMD) for training or in real world scenarios without computer graphics for training and uneven compensation, as demonstrated in [17]. The effect of SS training without graphical display in a real-world environment can also be studied.

V. Conclusion

This work describes integration of the SS with the TreadPort to provide haptic terrain display during gait in a VR environment. SS design features are summarized. Integration of the SS with the VR environment is accomplished by tracking foot position with motion capture, correlating that position to the VR world, and then commanding the SS to display terrain features at that location. Pilot studies with participants demonstrate desired haptic response. While conclusions need to be tempered due to the fact that the study is shown to be underpowered, we found statistically significant differences in subject type for HN speed, cadence, and ankle angle at 5% gait cycle. We also found differences related to shoe configuration for MTC and ankle angle for 15% and 25% gait cycle. Lastly, increased VR realism and difficulty of walking on cobblestone are reported, which was a major goal of this work. Normalized gait speed and cadence are not statistically different when walking on the SS-R versus actual cobble [32]. Therefore, the physical rendering of uneven terrain using the SS seems to introduce walking challenges and improved realism to the users in the TreadPort VR system. Such gait perturbations are useful for augmenting terrain display in traditional VR and potentially applicable for gait training among people with walking impediments or balance issues caused by diseases such as PD.

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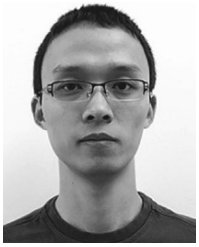

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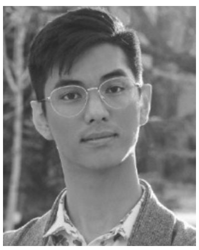

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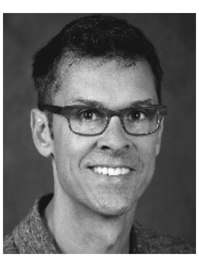

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