Gait & Posture 92 (2022) 442–448

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Virtual reality doorway and hallway environments alter gait kinematics in people with Parkinson disease and freezing

Amir Besharat [a,b,g,1], Sheri I. Imsdahl [c], Momona Yamagami [d], Nawat Nhan [e], Olivia Bellatin [f], Samuel A. Burden [d], Kathleen Cummer [c], Sujata D. Pradhan [c], Valerie E. Kelly [c,*]

[a] Veterans Affairs Puget Sound Health Care System, Seattle, WA, USA
[b] Department of Neurology, University of Washington, Seattle, WA, USA
[c] Department of Rehabilitation Medicine, University of Washington, Seattle, WA, USA
[d] Department of Electrical & Computer Engineering, University of Washington, Seattle, WA, USA
[e] Department of Mechanical Engineering, Gonzaga University, Spokane, WA, USA
[f] Department of Biomedical Engineering, Marquette University, Milwaukee, WI, USA
[g] Department of Neurology, University of Southern California, Los Angeles, CA, USA

ARTICLE INFO

Keywords:
Virtual reality
Freezing of gait
Parkinson disease
Gait analysis
Rehabilitation

ABSTRACT

Background: Many people with Parkinson disease (PD) experience freezing of gait (FoG), a transient gait disturbance associated with increased fall risk and reduced quality of life. Head-mounted virtual reality (VR) systems allow overground walking and can create immersive simulations of physical environments that induce FoG.

Research question: For people with PD who experience FoG (PD+FoG), are kinematic gait changes observed in VR simulations of FoG-provoking environments?

Methods: In a cross-sectional experiment, people with PD+FoG walked at their self-selected speed in a physical laboratory and virtual laboratory, doorway, and hallway environments. Motion analysis assessed whole-body kinematics, including lower extremity joint excursions, swing phase toe clearance, trunk flexion, arm swing, sagittal plane inclination angle, and spatiotemporal characteristics. One-way repeated measures analysis of variance was conducted to examine the effects of environment on gait variables, with planned contrasts between laboratory environments and the virtual doorway and hallway.

Results: Twelve participants with PD+FoG (mean age [standard deviation]=72.8 [6.5] years, disease duration=8.8 [8.9] years, 3 females) completed the protocol. The environment had significant and widespread effects on kinematic and spatiotemporal variables. Compared to the physical laboratory, reduced joint excursions were observed in the ankle, knee, and hip when walking in the virtual doorway and in the knee and hip when walking in the virtual hallway. In both the virtual doorway and hallway compared to the physical laboratory, peak swing phase toe clearance, arm swing, and inclination angle were reduced, and walking was slower, with shorter, wider steps.

Significance: Virtual doorway and hallway environments induced kinematic changes commonly associated with FoG episodes, and these kinematic changes are consistent with forward falls that are common during FoG episodes. Combined with the flexibility of emerging VR technology, this research supports the potential of VR applications designed to improve the understanding, assessment, and treatment of FoG.

1. Introduction

Freezing of gait (FoG) is an episodic gait disturbance, common among people with Parkinson disease (PD), in which a person is transiently unable to start or continue walking. Subjectively, people experiencing FoG describe feeling "glued to the floor," alluding to their inability to initiate or maintain forward progression despite efforts to continue walking [1]. The prevalence of FoG in PD is approximately

* Correspondence to: 1959 NE Pacific Street, Box 356490, Seattle, WA 98125, USA.
E-mail address: vekelly@uw.edu (V.E. Kelly).
[1] Present address: Department of Neurology, University of Southern California, Los Angeles, CA, USA.

https://doi.org/10.1016/j.gaitpost.2021.12.013
Received 22 June 2021; Received in revised form 24 November 2021; Accepted 9 December 2021
Available online 11 December 2021

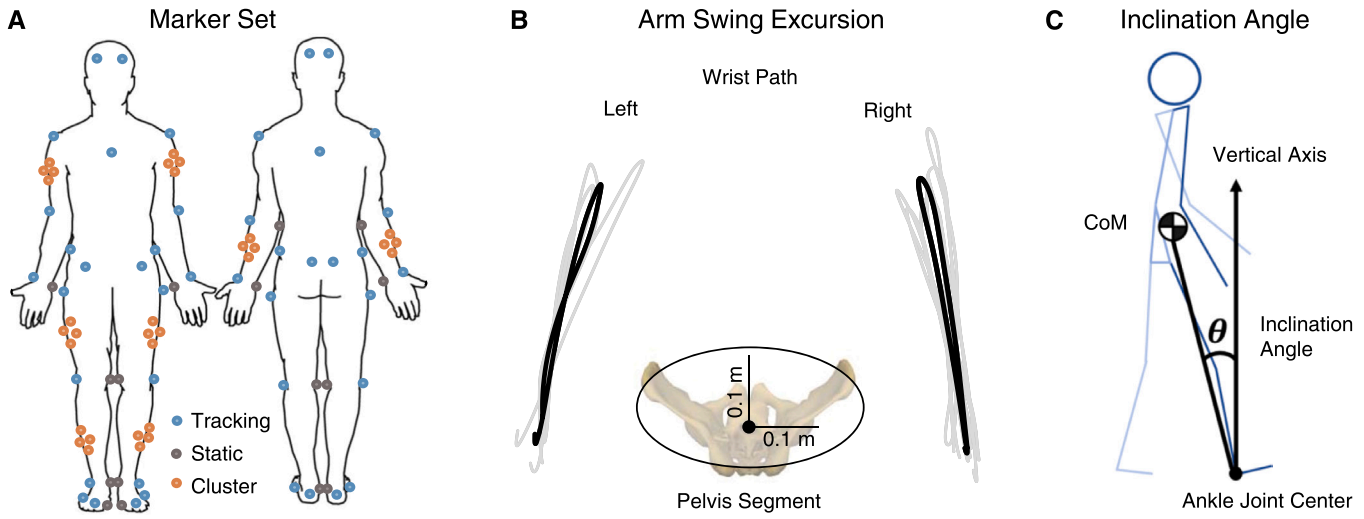

Fig. 1. (A) Whole-body marker set. Static calibration markers were used for biomechanical modeling and were removed for the walking trials. (B) Exemplar data of a participant's wrist path over a complete trial during the Phys-Lab condition. Traces from individual strides are plotted in gray, and the mean path is shown in black. (C) Illustrative definition of sagittal plane inclination angle. CoM: Center of mass.

25–50% and increases with longer disease duration [2–4]. For people with PD, FoG is associated with reduced quality of life, increased disability, and falls [2,4–6]. Despite the prevalence and impacts of FoG, its clinical management is challenging. As an episodic gait disorder, FoG is notoriously difficult to elicit in clinical or laboratory settings, making accurate assessment and effective treatment difficult [7]. FoG episodes are attenuated by dopaminergic medications for some people with PD but are unresponsive to medications for others, and worsening of FoG can occur with deep brain stimulation (DBS) [8].

Episodes of FoG are typically brief, lasting 10 s or less. During FoG episodes, gait is characterized by marked reductions in gait speed and step length, increased cadence, and reduced lower extremity joint excursion [9,10]. These gait abnormalities persist outside of FoG episodes. Compared to those without FoG, people with PD and FoG (PD+FoG) demonstrate reduced speed and step length and increased gait variability [11]. Kinematic abnormalities are also observed just prior to a FoG event, with lower extremity joint excursions reduced in the steps before a freezing episode compared to normal walking or a planned stop [10]. The changes observed during and preceding FoG episodes can increase the risk of anterior instability [12], and FoG is associated with both falls [5,6,13] and near falls [14]. Falls during FoG episodes are predominantly in the forward direction [13]. Among people with PD who experience recurrent falls, FoG is associated with forward falls that are more severe and that commonly occur during walking or turning [15].

Specific task, environment, cognitive, or affective factors can provoke FoG episodes. Confined spaces and doorways are among the most common factors inducing FoG [16], and replication of such environments with virtual reality (VR) has been used to study FoG [17,18]. Prior research incorporated projected virtual doorways or hallways to examine the underlying neural substrates of FoG [19]. Among people with PD+FoG, immersive virtual simulations of FoG-inducing environments cause slower walking with shorter, wider, and more variable steps compared to both physical laboratory and virtual laboratory environments [20,21]. However, prior work focused on spatiotemporal characteristics, and it is unclear if virtual simulations of FoG-provoking environments also induce the kinematic changes that characterize FoG episodes [10] and may contribute to falls.

The purpose of this study was to examine the effects of virtual doorways and hallways on gait kinematics among people with PD+FoG. Kinematic changes are critical to reflect whole-body motion, detect potential biomechanical instability, and describe clinically relevant gait changes. We hypothesized that, compared to physical and virtual laboratory environments, virtual doorway and hallway environments would exacerbate kinematic deficits, including reduced lower extremity joint excursions, toe clearance, and arm swing. We also anticipated that people with PD+FoG would demonstrate more pronounced forward flexion of the trunk and reduced sagittal plane inclination angle at initial contact, reflecting a relative position of the center of mass closer to the anterior limits of the base of support. The ability to replicate kinematic as well as spatiotemporal characteristics of FoG would support the utility of virtual environments for understanding the mechanisms and improving the clinical management of FoG.

2. Methods

2.1. Participants

Participants were recruited from a metropolitan region (Seattle, WA, USA) through the community, local clinics, and the Washington State Parkinson Disease Registry. Eligibility criteria included: a self-reported diagnosis of PD without dementia; self-reported or clinician-observed FoG; the ability to walk 400 m without assistance from a device or another person; no uncorrected vision or hearing deficits; and the absence of any medical conditions that would limit safe participation in the protocol. For people using DBS, consistent use and settings for the 4 weeks prior to the experimental session were required. Before participation in any study procedures, informed consent was obtained in accordance with approved University of Washington Institutional Review Board procedures.

2.2. Procedures

Overground walking was compared across physical and virtual environments using a cross-sectional experimental study design. After an initial phone screen to determine eligibility, participants completed a single experimental session at the University of Washington Amplifying Movement and Performance Laboratory. Walking was assessed in four conditions: physical laboratory, with no VR (Phys-Lab); VR simulation of the physical laboratory (VR-Lab); virtual doorway (VR-Door); and virtual hallway (VR-Hall). Participants first walked in the Phys-Lab condition to ensure appropriate motion capture quality, and then the order of VR conditions was randomized.

Virtual environments were developed using the Unity platform (Unity Technologies, San Francisco, CA, USA) and were viewed with an HTC Vive headset (HTC Corp., New Taipei City, Taiwan) using SteamVR

Table 1
Participant characteristics.

	PD+FoG (n = 12)
Demographic information	
Age (yrs)	72.8 (6.5)
Sex (F:M)	3:9
Height (m)	1.74 (0.08)
Weight (kg)	82.1 (13.9)
Medical comorbidities (#)	2.1 (1.8)
*MoCA	27 (18–29)
Mini-BEST	21.3 (3.4)
SSQ	15.0 (15.8)
PD-related information	
Time since diagnosis (yrs)	8.8 (8.9)
LEDD	903.2 (585.0)
UPDRS, Part III	42.5 (16.1)
*Hoehn & Yahr	2 (2–3)
NFoG	13.8 (3.7)

*Indicates median (range). All other values are mean (SD). Medical comorbidities (#) does not include PD. MoCA: Montreal Cognitive Assessment; Mini-BEST: Mini-Balance Evaluation Systems Test; SSQ: Simulator Sickness Questionnaire; LEDD: Levodopa-equivalent daily dose; UPDRS: Movement Disorder Society Unified Parkinson's Disease Rating Scale Part III, Motor Examination; NFoG: New Freezing of Gait Questionnaire.

software (Valve Corp., Bellevue, WA, USA). A researcher managed headset cables to prevent obstruction of participant movements. After walking in virtual environments, participants completed the Simulator Sickness Questionnaire (SSQ) to assess VR tolerance (range: 0–236) [22].

Prior to gait analysis, we collected demographic (age, height, weight, medical comorbidities) and PD-related information (time since diagnosis, medication and surgical treatment) in a focused interview. Trained clinicians then completed standardized assessments of PD severity, FoG, balance, and cognition. Motor severity was assessed with the Movement Disorder Society Unified Parkinson's Disease Rating Scale (MDS-UPDRS) Part III, Motor Examination subscale (range: 0–132) [23]. The New Freezing of Gait Questionnaire (NFoG) assessed the severity and impact of FoG (range: 0–28) [24]. The Mini-Balance Evaluation Systems Test (Mini-BEST) assessed balance (range: 0–28) [25]. Global cognitive function was assessed using the Montreal Cognitive Assessment (MoCA; range: 0–30) [26]. Participants were instructed to take their typical PD medications on the day of testing, and levodopa-equivalent daily dose (LEDD) was calculated for participants taking PD medications [27].

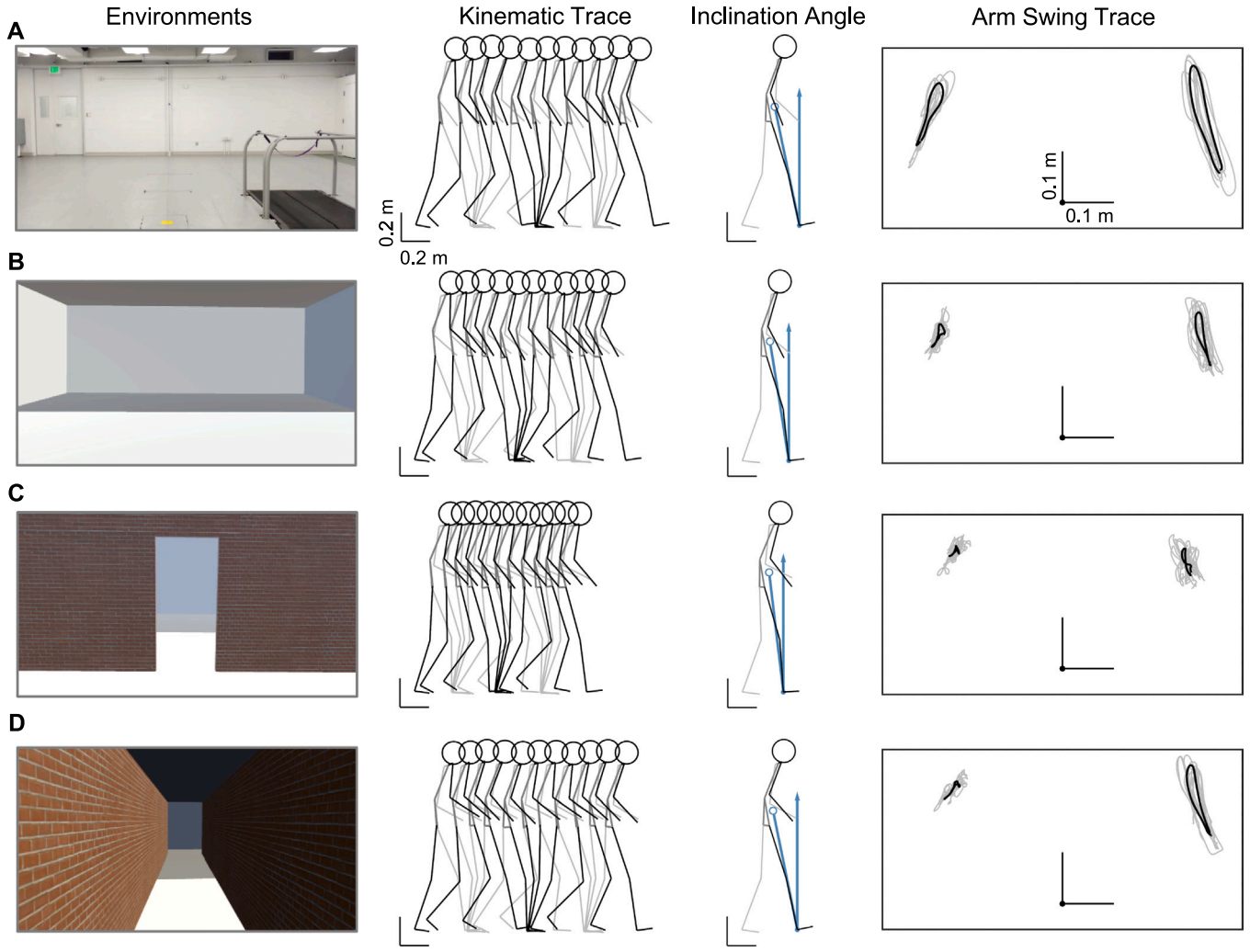

Fig. 2. Environments (column 1) used for the (A) Phys-Lab, (B) VR-Lab, (C) VR-Door, and (D) VR-Hall conditions. For a representative participant: corresponding sagittal plane kinematic traces are plotted at 10% increments for two consecutive gait cycles (column 2), sagittal plane inclination angle at initial contact is shown (column 3), and arm swing traces, expressed in the pelvis's local coordinate system (column 4), are plotted. For arm swing, paths from individual strides in the trial are shown in gray, and the mean path for each condition is shown in black.

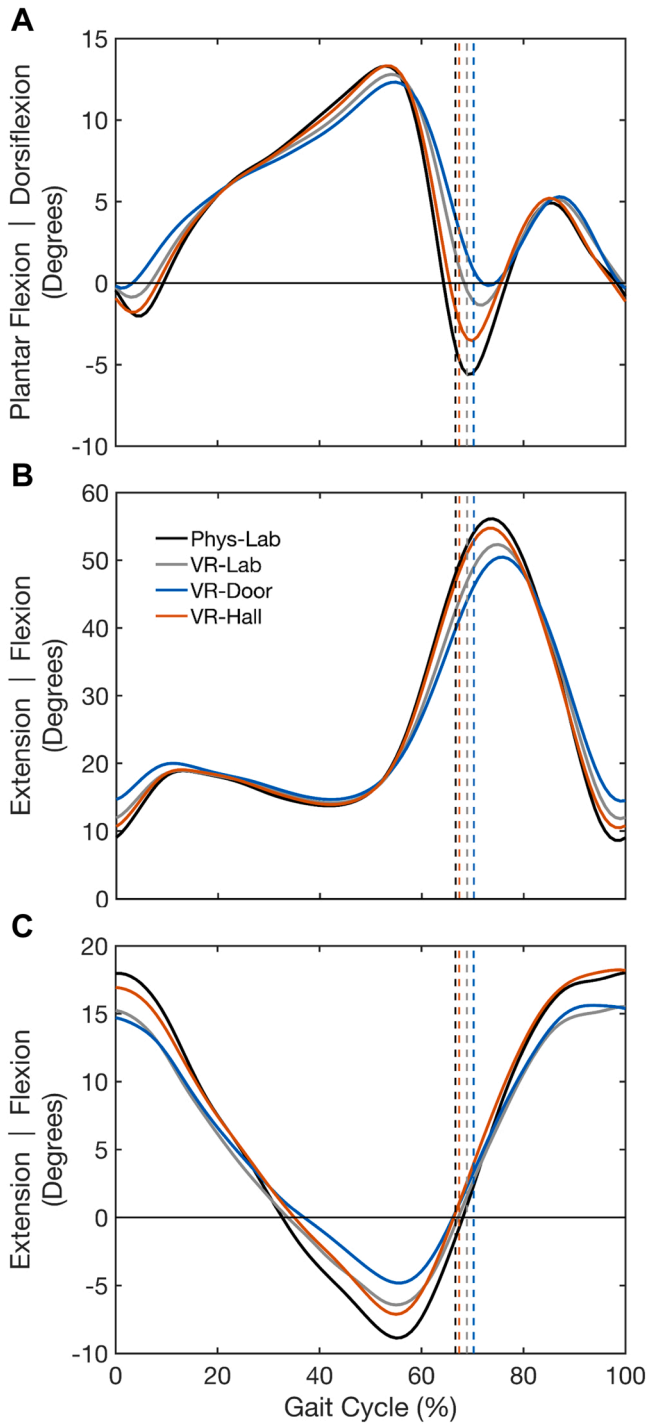

Fig. 3. Sagittal plane joint angles at the (A) ankle, (B) knee, and (C) hip for a single participant (same as in Fig. 2). Solid lines represent the average joint angle across all available strides and dotted lines represent the start of swing phase for the Phys-Lab (black), VR-Lab (gray), VR-Door (blue), and VR-Hall (orange) conditions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.3. Gait analysis

Retroreflective markers were placed bilaterally on the head, trunk, arms, and legs (Fig. 1A) and tracked at 120 Hz using 10 Oqus infrared motion capture cameras (Qualisys, Gothenburg, Sweden). The laboratory measured 10 m x 17 m, with motion capture and VR volumes of interest centered in the laboratory. In each condition, participants walked approximately 7 m at their self-selected speed, with gait analysis completed only for strides in the central 4–5 m of the walkway to minimize impacts of acceleration, deceleration, and turning.

Visual3D motion analysis software (C-Motion Inc., Rockville, MD, USA) was used to filter marker position data (zero-lag, fourth-order, low-pass Butterworth filter with 6 Hz cutoff), build a 13-segment biomechanical model, and compute all spatiotemporal and kinematic variables. For each participant, variables were calculated based on a minimum of 5 strides and an average of 10 strides per condition, with the exception of one participant who had data of sufficient quality for only three strides in the VR-Lab and four strides in the VR-Door condition. To understand the effects of environment on whole-body kinematics, we calculated sagittal plane ankle, knee, and hip joint excursions across the stride (maximum – minimum joint angle), mean trunk flexion, arm swing excursion, toe clearance, and sagittal plane inclination angle. Each variable was averaged across available right and left strides because prior research [28] and data inspection revealed minimal differences between sides. Toe clearance was defined as the distance from the distal foot to the ground and calculated: (1) at mid-swing (operationalized as the point of peak knee flexion) and (2) as swing phase maximum [28]. Arm swing was quantified as the total path distance traveled by the wrist relative to the pelvis over a stride [29] (Fig. 1B), with the origin of the pelvis's local coordinate system defined as the midpoint between the iliac crest markers. Sagittal plane inclination angle was calculated as the angle, at initial contact, between a vertical axis through the calculated ankle joint center and a line connecting the center of mass and ankle joint center [30] (Fig. 1 C). We also characterized the effects of environment on spatiotemporal variables representing independent domains of gait [31], including pace (gait speed, step length), rhythm (step time), variability (step length variability, measured as standard deviation, SD [32]), asymmetry (step time asymmetry), and postural control (step width, % of gait cycle spent in double limb support). The frequency of festination was determined by calculating the percent of steps in each VR condition with step length < 3 SD below the mean in the Phys-Lab condition.

2.4. Statistical analysis

All statistical analyses were completed in SPSS (IBM SPSS Statistics, v19.0, Armonk, NY, USA). Descriptive statistics summarized participant characteristics. After testing assumptions of normality and sphericity, a one-way repeated measures analysis of variance (ANOVA) was conducted to determine whether there was a statistically significant effect of environment on spatiotemporal and kinematic variables, with significance set at $\alpha = 0.05$. Effect sizes are reported using partial eta squared (η_p^2). Data from one participant were excluded from the analysis of arm swing excursion and inclination angle because that participant required handheld assist when wearing the VR headset. Violations of sphericity were corrected using Greenhouse-Geisser for festination, knee excursion, and mean trunk flexion ANOVAs. For ANOVAs with significant main effects, four planned contrasts were used to determine the specific effects of VR-Door and VR-Hall environments compared to laboratory environments (Phys-Lab and VR-Lab). Significance was set at $\alpha = 0.05$ for this exploratory work, and only statistically significant results are reported below.

3. Results

3.1. Participant characteristics

Demographic and PD-related characteristics for the 12 enrolled participants are summarized in Table 1. One participant had DBS, which was turned on throughout the session. Participants had moderate PD, with evidence of cognitive impairment, based on MoCA scores, and balance impairments, based on MiniBEST scores. Two participants were not taking PD medications, and one participant completed testing in the

Table 2
Effect of VR environments on spatiotemporal and kinematic gait variables.

	Phys-Lab	VR-Lab	VR-Door	VR-Hall	*F*	*p*	η_p^2
Kinematic variables							
Ankle excursion (°)	27.0 (5.6)	25.0 (6.3)	24.5 (5.5)*	25.9 (6.2)	4.81	.007	.30
Knee excursion (°)	55.7 (5.8)	53.0 (8.9)	51.6 (7.4)*	53.5 (6.6)*	5.43	.01	.33
Hip excursion (°)	33.0 (5.8)	30.9 (7.9)	29.6 (6.2)*	30.5 (6.2)*	9.29	< 0.001	.46
Trunk flexion (°)	11.4 (8.2)	11.3 (8.8)	12.9 (9.2)	12.3 (8.9)* †	3.85	.05	.26
Toe clear., MS (cm)	3.7 (1.6)	3.7 (1.5)	3.6 (1.6)	3.5 (1.5)	2.38	.09	.18
Peak toe clear. (cm)	12.4 (2.7)	11.3 (3.0)	10.7 (2.8)	11.1 (2.8)	11.4	< 0.001	.51
Arm swing (m)	0.47 (0.22)	0.39 (0.24)	0.34 (0.20)*	0.37 (0.20)*	6.80	.001	.40
Inclination angle (°)	12.9 (2.9)	11.2 (4.2)	10.6 (3.7)*	11.4 (3.4)*	8.08	< 0.001	.45
Spatiotemporal variables							
Gait speed (m/s)	0.95 (0.17)	0.82 (0.23)	0.80 (0.20)*	0.86 (0.18)*	8.62	< 0.001	.44
Step length (m)	0.53 (0.08)	0.47 (0.12)	0.45 (0.10)*	0.48 (0.10)*	11.53	< 0.001	.51
Step time (s)	0.57 (0.07)	0.59 (0.07)	0.58 (0.06)	0.56 (0.05)†	3.05	.04	.22
Step length var. (m)	0.03 (0.01)	0.03 (0.01)	0.05 (0.02)* †	0.04 (0.01)	3.97	.02	.27
Step time asym. (s)	0.03 (0.02)	0.02 (0.01)	0.03 (0.02)	0.02 (0.02)	0.48	.50	.04
Step width (m)	0.13 (0.03)	0.15 (0.03)	0.15 (0.03)*	0.14 (0.03)*	9.41	< 0.001	.46
DLS (%)	31.9 (3.4)	34.8 (5.3)	35.1 (5.2)*	34.0 (5.2)*	4.76	.007	.30
Festination (%)	0.0 (0.0)	23.4 (34.9)	31.9 (28.4)*	11.2 (9.9)*	4.64	.02	.30

DLS: Double limb support; MS: Mid-swing. Values for each condition are mean (SD). F(3, 33) values, p-values, and η_p^2 are for one-way repeated measures ANOVA results. For arm swing path and inclination angle, one participant was excluded from the analysis resulting in F(3, 30). Greenhouse-Geisser correction resulted in F(2.0, 21.8) for knee excursion, F(1.6, 17.2) for trunk flexion, and F(1.9, 20.9) for festination. Symbols indicate post hoc differences determined with planned contrasts:
* Significant difference compared to the Phys-Lab condition ($p < .05$).
† Significant difference compared to the VR-Lab condition ($p < .05$).

morning prior to taking their first dose of medications (900 min since last dose). For the remaining nine participants, the average time from their last dose of medications to the start of testing was 186 (90) minutes. At the completion of the session, low SSQ scores indicated good tolerance of VR environments.

3.2. Kinematic variables

Figs. 2 and 3 provide an example of gait, inclination angle, arm swing, and lower extremity joint excursions for a representative participant. Overt FoG episodes did not occur for any participant, and all analyses below reflect walking while maintaining forward progression. Environment significantly affected all lower extremity joint excursions, arm swing, and sagittal plane inclination angle (Table 2). Toe clearance at mid-swing was not affected by environment, but peak toe clearance was. The effect on trunk flexion was marginally significant. Planned contrasts (Table 3) showed that the VR-Door condition resulted in reduced ankle, knee, and hip excursions compared to the Phys-Lab. In the VR-Hall condition, only knee and hip excursions were lower than in the Phys-Lab. Trunk flexion was increased in the VR-Hall condition compared to both the Phys-Lab and the VR-Lab. Peak toe clearance, arm swing, and inclination angle were reduced in both the VR-Door and VR-Hall conditions compared to the Phys-Lab.

3.3. Spatiotemporal variables

Environment significantly affected spatiotemporal variables representing pace, rhythm, variability, postural control, and festination, but not asymmetry (Table 2). Planned contrasts (Table 3) showed that the VR-Door condition resulted in reduced gait speed and step length and increased step length variability, step width, double limb support, and festination compared to the Phys-Lab. Step length variability was also increased in the VR-Door compared to the VR-Lab. The VR-Hall condition resulted in reduced gait speed and step length and increased step width, double limb support, and festination compared to the Phys-Lab. In addition, step time was shorter in the VR-Hall compared to the VR-Lab.

4. Discussion

This study examined kinematic changes among people with PD+FoG when walking in virtual doorway and hallway environments compared to laboratory environments. Compared to the virtual laboratory, gait changes in the doorway and hallway environments were largely limited to spatiotemporal measures. Compared to the physical laboratory, there were widespread kinematic and spatiotemporal changes in the virtual doorway and hallway environments. In virtual doorway and hallway environments, people with PD+FoG demonstrated reduced lower extremity joint excursions, peak toe clearance, arm swing, and sagittal plane inclination angle. Gait speed was reduced, with shorter, wider, and more variable steps, increased double limb support, and more frequent festination.

Our hypothesis that virtual doorways and hallways would elicit whole-body kinematic changes was partially supported. In this study, average lower extremity joint excursions in the physical laboratory were comparable to values previously reported during forward walking in people with PD+FoG [28,33] and people with PD in the off-medication state [34]. Consistent with our hypothesis, joint excursions decreased when walking in virtual doorway and hallway environments compared to the physical laboratory, which aligns with prior research demonstrating reduced joint excursions in the strides prior to a freezing episode [10]. In addition, peak toe clearance, arm swing, and sagittal plane inclination angle decreased in virtual doorway and hallway environments compared to the physical laboratory. Trunk flexion increased only in the virtual hallway compared to the physical and virtual laboratories.

Reduced inclination angle could result from a combination of shorter steps and increased forward trunk flexion. In this study, step length decreased in virtual doorway and hallway environments compared to the physical laboratory. Trunk flexion increased, though this was significant only in the virtual hallway. The whole-body kinematic changes we observed, reflected in a reduced inclination angle, could contribute to biomechanical instability as the center of mass approaches the anterior limits of the base of support. Our findings align with recent research demonstrating anterior instability, reflected in a reduced distance between the center of mass and base of support, in people with PD+FoG compared to those without FoG [12]. These biomechanical changes are consistent with research demonstrating that falls associated with FoG episodes are predominantly in the forward direction [13] and that more severe freezing is associated with forward falls [15].

The use of doorways to elicit FoG is well established. When approaching physical doorways, people with PD+FoG walk more slowly than healthy older adults and people with PD who do not freeze, and

Table 3
Planned contrasts between FoG-provoking VR environments and laboratory environments.

	VR-Door		VR-Hall	
Compared to Phys-Lab	Mean diff. (95% CI)	*p*	Mean diff. (95% CI)	*p*
Kinematic variables				
Ankle excursion (°)	2.5 (1.3, 3.8)	.001	–	–
Knee excursion (°)	4.1 (1.8, 6.5)	.003	2.2 (1.0, 3.5)	.002
Hip excursion (°)	3.3 (2.0, 4.7)	< 0.001	2.5 (1.7, 3.3)	< 0.001
Trunk flexion (°)	–	–	−0.9 (−1.8, −0.01)	.048
Peak toe clearance (cm)	1.7 (1.0, 2.3)	< 0.001	1.2 (0.9, 1.6)	< 0.001
Arm swing (m)	0.13 (0.04, 0.21)	.007	0.10 (0.03, 0.16)	.009
Inclination angle (°)	2.2 (1.2, 3.3)	.001	1.5 (0.9, 2.1)	< 0.001
Spatiotemporal variables				
Gait speed (m/s)	0.15 (0.09, 0.22)	< 0.001	0.09 (0.01, 0.16)	.03
Step length (m)	0.08 (0.05, 0.11)	< 0.001	0.05 (0.03, 0.08)	< 0.001
Step length var. (m)	−0.014 (−0.025, −0.003)	.02	–	–
Step width (m)	−0.02 (−0.02, −0.01)	.001	−0.01 (−0.02, 0.00)	.03
DLS (%)	−3.2 (−5.0, −1.4)	.002	−2.1 (−4.2, 0.0)	.048
Festination (%)	−31.9 (−50.0, −13.9)	.003	−11.2 (−17.4, −4.9)	.002
Compared to VR-Lab	Mean diff. (95% CI)	*p*	Mean diff. (95% CI)	*p*
Kinematic variables				
Trunk flexion (°)	–	–	−1.1 (−1.6, −0.5)	.002
Spatiotemporal variables				
Step time (s)	–	–	0.03 (0.00, 0.05)	.03
Step length var. (m)	−0.015 (−0.025, −0.004)	.01	–	–

DLS: Double limb support. Significant results from planned contrasts, showing mean difference (95% confidence interval, CI) and p-values. Phys-Lab and VR-Lab were the reference conditions for all contrasts.

those with PD+FoG also exhibit gait changes characteristic of freezing, such as reduced step length and increased step variability [35,36]. These findings have been replicated using virtual doorways in immersive VR environments [21,37], suggesting that virtual doorways are a reliable proxy for their physical counterparts and may be particularly provocative for FoG.

Virtual environments offer several advantages as a platform for understanding, assessing, and treating FoG. With VR technology, it is possible to create both standardized clinical tools and customized environments that incorporate elements that provoke or ameliorate FoG for a given person. For example, in virtual environments, one can manipulate the width of doorways or add perceptual aspects, like complex surface textures. Visual cues that alleviate FoG, such as lines perpendicular to the walking path, can be incorporated into FoG-provoking environments. The flexibility of VR environments supports the potential of this technology to inform research and rehabilitation of FoG and other gait impairments in PD [17,18]. In this study, the replication of kinematic changes associated with FoG in virtual doorways and hallways highlights potential biomechanical markers of instability and fall risk. Accurate replication of the gait characteristics associated with FoG is essential to the clinical utility of VR applications designed to assess and treat FoG, particularly if reduced fall risk is a therapeutic goal. Future development and research in this area is merited, with an initial need to understand the acceptability, safety, and efficacy of such tools in supervised clinical or research settings before broader implementation is examined.

Limitations of the current work should be taken into consideration. First, medication status varied across participants; thus, it is not possible to determine the specific effects of medication from this study. Future research comparing off-medication and on-medication gait changes could elucidate whether kinematic changes in FoG-provoking VR environments are more substantial in the off-medication state. Second, given the high level of data quality required for kinematic analyses, an average of 10 strides per person per condition were available. This compares favorably to other kinematic studies of FoG [28,33] but is lower than the recommended number of strides for optimizing reliability of spatiotemporal measures, particularly variability [32]. Spatiotemporal and kinematic changes were observed primarily between the virtual doorway and hallway conditions compared to the physical laboratory. Limited exposure to immersive VR and the lack of an avatar, or digital representation of the body, may have impacted the current findings. Longer acclimation to VR environments is important for future studies, and the use of avatars can provide valuable feedback about a person's position and movements within the virtual space. The environments in this study were relatively simple, with only static VR elements. More sophisticated VR environments could create more realistic and immersive experiences. Finally, this study was limited to environments designed to provoke FoG during forward walking. More complex tasks, such as gait initiation, side-stepping, turning, or stepping backward, can also trigger FoG episodes. The use of a head-mounted, immersive system allows overground walking in any direction, and virtual simulations of environments that require these types of mobility tasks can be created with VR. Future work should examine the utility of VR across a broader repertoire of movement tasks causing FoG.

For people with PD, FoG has profound consequences, including falls and reduced quality of life. However, the fact that FoG is difficult to elicit in clinical and laboratory settings contributes to current shortcomings in the clinical management of FoG. This study demonstrates that virtual simulations of FoG-provoking environments can induce kinematic changes associated with FoG episodes and suggests the sagittal plane inclination angle as a potential biomechanical marker of increased fall risk associated with FoG. Future research examining VR applications to assess and treat FoG is merited, given the flexibility of this platform to replicate FoG-provoking environments and its ability to provoke spatiotemporal and kinematic characteristics of FoG.

Funding

During the period of work on this project, Dr. Besharat was supported by the Veterans Affairs Advanced Fellowship Program in Parkinson's Disease. Momona Yamagami, Olivia Bellatin, and Nawat Nhan received fellowships and grants from the University of Washington. Funding sources were not involved in the study design; collection, analysis, or interpretation of data; or manuscript preparation and submission. This research was supported by the University of Washington College of Engineering.

Declaration of competing interest

The authors report no conflicts of interest.

Acknowledgements

We wish to thank all of our participants for their involvement with this research, Samuel Jewell and Christopher Villarosa for their assistance with data collection, and the Washington State Parkinson Disease Registry for their assistance with recruitment.

References

[1] J.G. Nutt, B.R. Bloem, N. Giladi, M. Hallett, F.B. Horak, A. Nieuwboer, Freezing of gait: moving forward on a mysterious clinical phenomenon, Lancet Neurol. 10 (8) (2011) 734–744.
[2] M. Amboni, F. Stocchi, G. Abbruzzese, L. Morgante, M. Onofrj, S. Ruggieri, M. Tinazzi, M. Zappia, M. Attar, D. Colombo, L. Simoni, A. Ori, P. Barone, A. Antonini, Prevalence and associated features of self-reported freezing of gait in Parkinson disease: The DEEP FOG study, Park. Relat. Disord. 21 (6) (2015) 644–649.
[3] E.B. Forsaa, J.P. Larsen, T. Wentzel-Larsen, G. Alves, A 12-year population-based study of freezing of gait in Parkinson's disease, Park. Relat. Disord. 21 (3) (2015) 254–258.
[4] S. Perez-Lloret, L. Negre-Pages, P. Damier, A. Delval, P. Derkinderen, A. Destée, W. G. Meissner, L. Schelosky, F. Tison, O. Rascol, Prevalence, determinants, and effect on quality of life of freezing of gait in Parkinson disease, JAMA Neurol. 71 (7) (2014) 884–890.
[5] G.K. Kerr, C.J. Worringham, M.H. Cole, P.F. Lacherez, J.M. Wood, P.A. Silburn, Predictors of future falls in Parkinson disease, Neurology 75 (2) (2010) 116–124.
[6] A. Ashburn, E. Stack, C. Ballinger, L. Fazakarley, C. Fitton, The circumstances of falls among people with Parkinson's disease and the use of Falls Diaries to facilitate reporting, Disabil. Rehabil. 30 (16) (2008) 1205–1212.
[7] C. Barthel, E. Mallia, B. Debû, B.R. Bloem, M.U. Ferraye, The practicalities of assessing freezing of gait, J. Park. Dis. 6 (4) (2016) 667–674.
[8] J. Nonnekes, A.H. Snijders, J.G. Nutt, G. Deuschl, N. Giladi, B.R. Bloem, Freezing of gait: a practical approach to management, Lancet Neurol. 14 (7) (2015) 768–778.
[9] A. Nieuwboer, R. Dom, W. De Weerdt, K. Desloovere, S. Fieuws, E. Broens-Kaucsik, Abnormalities of the spatiotemporal characteristics of gait at the onset of freezing in Parkinson's disease, Mov. Disord. 16 (6) (2001) 1066–1075.
[10] A. Nieuwboer, F. Chavret, A.M. Willems, K. Desloovere, Does freezing in Parkinson's disease change limb coordination? A kinematic analysis, J. Neurol. 254 (9) (2007) 1268–1277.
[11] M.T. Barbe, M. Amarell, A.H. Snijders, E. Florin, E.L. Quatuor, E. Schönau, G. R. Fink, B.R. Bloem, L. Timmermann, Gait and upper limb variability in Parkinson's disease patients with and without freezing of gait, J. Neurol. 261 (2) (2014) 330–342.
[12] H. Urakami, Y. Nikaido, K. Kuroda, H. Ohno, R. Saura, Y. Okada, Forward gait instability in patients with Parkinson's disease with freezing of gait, Neurosci. Res. 173 (2021) 80–89.
[13] Y. Okuma, A.L. Silva de Lima, J. Fukae, B.R. Bloem, A.H. Snijders, A prospective study of falls in relation to freezing of gait and response fluctuations in Parkinson's disease, Park. Relat. Disord. 46 (2018) 30–35.
[14] T. Gazibara, D. Kisic Tepavcevic, M. Svetel, A. Tomic, I. Stankovic, V.S. Kostic, T. Pekmezovic, Near-falls in people with Parkinson's disease: circumstances, contributing factors and association with falling, Clin. Neurol. Neurosurg. 161 (2017) 51–55.
[15] J. Youn, Y. Okuma, M. Hwang, D. Kim, J.W. Cho, Falling direction can predict the mechanism of recurrent falls in advanced Parkinson's disease, Sci. Rep. 7 (1) (2017) 3921.
[16] S. Rahman, H.J. Griffin, N.P. Quinn, M. Jahanshahi, The factors that induce or overcome freezing of gait in Parkinson's disease, Behav. Neurol. 19 (3) (2008) 127–136.
[17] B. Bluett, E. Bayram, I. Litvan, The virtual reality of Parkinson's disease freezing of gait: a systematic review, Park. Relat. Disord. 61 (2018) 26–33.
[18] C.G. Canning, N.E. Allen, E. Nackaerts, S.S. Paul, A. Nieuwboer, M. Gilat, Virtual reality in research and rehabilitation of gait and balance in Parkinson disease, Nat. Rev. Neurol. 16 (8) (2020) 409–425.
[19] E. Matar, J.M. Shine, M. Gilat, K.A. Ehgoetz Martens, P.B. Ward, M.J. Frank, A. A. Moustafa, S.L. Naismith, S.J.G. Lewis, Identifying the neural correlates of doorway freezing in Parkinson's disease, Hum. Brain Mapp. 40 (7) (2019) 2055–2064.
[20] L.I. Gómez-Jordana, J. Stafford, C.E. Peper, C.M. Craig, Crossing virtual doors: a new method to study gait impairments and freezing of gait in Parkinson's disease, Park. Dis. 2018 (2018) 2957427–2957428.
[21] M. Yamagami, S. Imsdahl, K. Lindgren, et al., Effects of virtual reality environments on overground walking in people with Parkinson disease and freezing of gait, Disabil. Rehabil. Assist. Technol. (2020) 1–8.
[22] R.S. Kennedy, N.E. Lane, Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness, Int. J. Aviat. Psychol. 3 (3) (1993) 203–220.
[23] C.G. Goetz, B.C. Tilley, S.R. Shaftman, G.T. Stebbins, S. Fahn, P. Martinez-Martin, W. Poewe, C. Sampaio, M.B. Stern, R. Dodel, B. Dubois, R. Holloway, J. Jankovic, J. Kulisevsky, A.E. Lang, A. Lees, S. Leurgans, P.A. LeWitt, D. Nyenhuis, C. W. Olanow, O. Rascol, A. Schrag, J.A. Teresi, J.J. van Hilten, N. LaPelle, F. Movement Disorder Society UPDRS Revision Task, Movement disorder society-sponsored revision of the unified Parkinson's disease rating scale (MDS-UPDRS): scale presentation and clinimetric testing results, Mov. Disord. 23 (15) (2008) 2129–2170.
[24] A. Nieuwboer, L. Rochester, T. Herman, W. Vandenberghe, G.E. Emil, T. Thomaes, N. Giladi, Reliability of the new freezing of gait questionnaire: agreement between patients with Parkinson's disease and their carers, Gait Posture 30 (4) (2009) 459–463.
[25] F. Franchignoni, F. Horak, M. Godi, A. Nardone, A. Giordano, Using psychometric techniques to improve the balance evaluation systems test: the mini-BESTest, J. Rehabil. Med. 42 (4) (2010) 323–331.
[26] Z.S. Nasreddine, N.A. Phillips, V. BÃ©dirian, S. Charbonneau, V. Whitehead, I. Collin, J.L. Cummings, H. Chertkow, The montreal cognitive assessment, MoCA: a brief screening tool for mild cognitive impairment, J. Am. Geriatr. Soc. 53 (4) (2005) 695–699.
[27] C.L. Tomlinson, R. Stowe, S. Patel, C. Rick, R. Gray, C.E. Clarke, Systematic review of levodopa dose equivalency reporting in Parkinson's disease, Mov. Disord. 25 (15) (2010) 2649–2653.
[28] M. Son, S.M. Cheon, C. Youm, Y. Kim, J.W. Kim, Impacts of freezing of gait on forward and backward gait in Parkinson's disease, Gait Posture 61 (2018) 320–324.
[29] M.D. Lewek, R. Poole, J. Johnson, O. Halawa, X. Huang, Arm swing magnitude and asymmetry during gait in the early stages of Parkinson's disease, Gait Posture 31 (2) (2010) 256–260.
[30] H.J. Lee, L.S. Chou, Detection of gait instability using the center of mass and center of pressure inclination angles, Arch. Phys. Med. Rehabil. 87 (4) (2006) 569–575.
[31] S. Lord, B. Galna, L. Rochester, Moving forward on gait measurement: toward a more refined approach, Mov. Disord. 28 (11) (2013) 1534–1543.
[32] B. Galna, S. Lord, L. Rochester, Is gait variability reliable in older adults and Parkinson's disease? Towards an optimal testing protocol, Gait Posture 37 (4) (2013) 580–585.
[33] P.S. Myers, K.S. Rawson, E.C. Harrison, A.P. Horin, E.N. Sutter, M.E. McNeely, G. M. Earhart, Cross-sectional analysis of backward, forward, and dual task gait kinematics in people with Parkinson disease with and without freezing of gait, J. Appl. Biomech. 36 (2020) 1–11.
[34] M. Morris, R. Iansek, J. McGinley, T. Matyas, F. Huxham, Three-dimensional gait biomechanics in Parkinson's disease: evidence for a centrally mediated amplitude regulation disorder, Mov. Disord. 20 (1) (2005) 40–50.
[35] Q.J. Almeida, C.A. Lebold, Freezing of gait in Parkinson's disease: a perceptual cause for a motor impairment? J. Neurol. Neurosurg. Psychiatry 81 (5) (2010) 513–518.
[36] D. Cowie, P. Limousin, A. Peters, M. Hariz, B.L. Day, Doorway-provoked freezing of gait in Parkinson's disease, Mov. Disord. 27 (4) (2012) 492–499.
[37] L.I. Gómez-Jordana, J. Stafford, C.E. Peper, C.M. Craig, Crossing virtual doors: a new method to study gait impairments and freezing of gait in Parkinson's disease, Park. Dis. 2018 (2018) 1–8.