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ORIGINAL RESEARCH

Effects of virtual reality environments on overground walking in people with Parkinson disease and freezing of gait

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ABSTRACT

Background: Freezing of gait (FoG) is a common target of rehabilitative interventions for people with Parkinson disease (PD). Virtual reality (VR) holds potential for advancing research and clinical management of FoG through flexible creation of FoG-provoking environments that are not easily or safely replicated in the clinic.

Objective: The aim of this study was to investigate whether VR environments that replicate FoG-provoking situations would exacerbate gait impairments associated with FoG compared to unobstructed VR and physical laboratory environments.

Methods: Gait characteristics (pace, rhythm, variability, asymmetry, and postural control domains) and festination were measured using motion capture while people with PD walked in VR environments based on FoG-provoking situations (doorway, hallway, and crowd environments) compared to unobstructed VR and physical laboratory environments. The effect of VR environments was assessed using one-way repeated measures ANOVAs with planned contrasts.

Results: Ten participants (mean age 74.1 years, 3 females, Hoehn and Yahr stage 2–3) with PD who self-reported FoG participated. Gait speed and step length were reduced in all VR environments compared to the physical laboratory. Step width was wider, step length was more variable, and festination was more common for some of the VR environments compared to the physical laboratory environment. Compared to the unobstructed virtual laboratory environment, step length was more variable in VR crowd and doorway environments.

Conclusions: The exacerbation of gait impairments that are characteristic precursors of FoG in FoG-provoking VR environments supports the potential utility of VR technology in the assessment and treatment of gait impairments in PD.

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Freezing of gait; gait analysis; rehabilitation; virtual reality; Parkinson disease

➤ IMPLICATIONS FOR REHABILITATION

- Freezing increases fall risk and reduces quality of life in Parkinson disease (PD).
- Virtual reality (VR) can simulate visuospatial environments that provoke freezing.
- Immersive VR doorway, hallway, and crowd environments were developed.
- Gait speed slowed when people with PD walked overground in all VR environments.
- Step variability and festination increased in freeze-provoking environments.

Introduction

Freezing of gait (FoG) is a prevalent and consequential motor disturbance in Parkinson disease (PD), leading to increased fall risk, mobility limitations, and reduced quality of life [1,2]. FoG is defined as the "brief, episodic absence or marked reduction of forward progression of the feet despite the intention to walk" and is typically preceded by increased cadence and decreased step length [3]. Impaired visuospatial function is associated with FoG [4,5] and could make it difficult for people with FoG to integrate visuospatial information in certain environments like doorways, hallways, and crowds, which are commonly reported to provoke FoG [6,7]. Given the significant adverse consequences associated with FoG, there is a critical need for improved assessment and intervention approaches for both FoG and the gait impairments that precede FoG. However, despite the fact that over half of people with PD self-report FoG [8], episodes of FoG are difficult to reproduce in clinical and research settings.

Virtual reality (VR) is an emerging tool that may enhance preventative and rehabilitative approaches for FoG. Non-immersive VR combined with a seated stepping task has been used in neuroimaging studies that examine the underlying mechanisms of freezing [9–12]. In combination with treadmill training, non-immersive VR has been used to treat gait impairments in PD [13–15]. Immersive VR has been used less frequently in studies aimed at improving gait impairments [16] and assessing FoG [17]. Though there are many causes of FoG, VR may be a particularly effective tool for studying FoG because specific visuospatial environments that provoke FoG can be created and manipulated without physical obstructions that can impede safe mobility or guarding. While it can be difficult to physically recreate FoG-provoking environments in the clinic or laboratory, VR enables the

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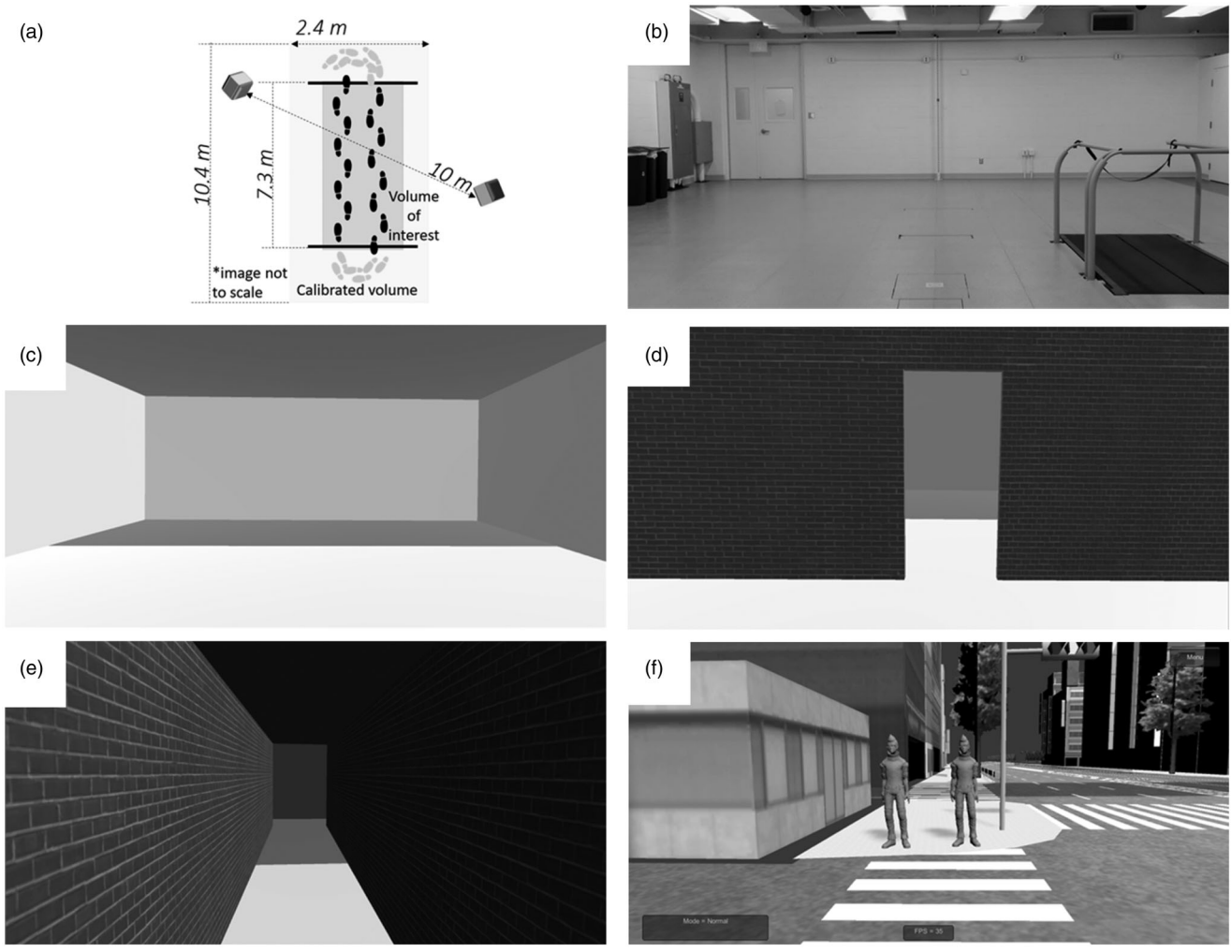

Figure 1. (a) Schematic of the laboratory: participants walked overground in a straight line back and forth in between two lines marked on the floor. (b) Laboratory for Physical-Lab condition. (c) VR-Lab environment, (d) VR-Door environment. (e) VR-Hall environment. (f) VR-Crowd environment.

creation of complex, realistic, and dynamic visuospatial environments that can be manipulated according to the needs and abilities of each person.

The current study used immersive VR technology to simulate environments that commonly provoke FoG – doorway, hallway, and crowd scenes – and measured their impact on gait during overground walking compared to control environments of physical and virtual laboratories. As a first step towards examining the potential of VR applications for research and clinical management of FoG, we sought to understand how immersive VR environments designed to provoke FoG impact overground walking among people with PD who self-reported FoG. We hypothesized that gait impairments would be exacerbated when participants walked in VR simulations of FoG-provoking environments compared to virtual or physical laboratory environments. Immersive VR is an immature but rapidly progressing technology, and the ability to replicate physical environments that provoke FoG support its potential as a tool for researchers seeking to better understand mechanisms of FoG and for clinicians seeking improved assessment and treatment options for FoG.

Methods

Participants

Participants were recruited through the Washington State Parkinson Disease Registry from April 2018–May 2019. An initial phone screen of interested individuals assessed their fit with study eligibility criteria: (1) a diagnosis of PD; (2) self-reported FoG; (3) self-reported ability to walk 400 m without assistance from a device or another person; (4) no diagnosis of dementia; (5) no uncorrected vision or hearing problems; (6) no other medical conditions that would limit the ability to participate in the protocol. All participants provided informed consent before participating, in accordance with applicable Institutional Review Board procedures.

Procedures

A cross-sectional study design was used to compare overground walking in a physical laboratory environment, a virtual laboratory environment, and three VR environments that simulated environments reported to provoke FoG [7]. A convenience sample of ten participants was predetermined as achievable given the eligibility criteria and the number of potential participants in the catchment area. Participants completed a single experimental session at the University of Washington Amplifying Movement and Performance Laboratory. Participants were asked to take all their usual medications, including any for PD, for the session. In an interview, participants provided demographic and health information, including age, sex, height, weight, medical comorbidities, and current medications. A clinical examination assessed motor signs of PD, FoG, global cognition, balance, balance confidence, and self-reported

fall history. The severity of motor signs was assessed using the Movement Disorder Society Unified Parkinson's Disease Rating Scale (MDS-UPDRS) Part III, Motor Examination subscale [18]. The presence, severity, and impact of FoG on activities of daily life were assessed using the New Freezing of Gait (NFoG) Questionnaire, scored without the use of the video [19]. Global cognition was assessed using the Montreal Cognitive Assessment (MoCA) [20], a brief screening tool with excellent discrimination for mild cognitive impairment and dementia in PD [21]. Balance was assessed using the Mini-Balance Evaluation Systems Test (Mini-BEST) [22], a 14-item performance-based measure with excellent concurrent validity compared to the Berg Balance Scale and excellent test-retest reliability and inter-rater reliability in PD [23]. Balance confidence was assessed using the Activities-specific Balance Confidence (ABC) Scale [24], a subjective measure of confidence in performing a variety of ambulatory activities without losing one's balance or becoming unsteady, with excellent test-retest reliability in PD [25]. Fall history was assessed over the prior three-month period, with a fall defined as "an unexpected event in which the participant comes to rest on the ground, floor, or lower level" [26].

Walking environments

Participants were asked to walk overground at their self-selected speed over a firm, level surface. Participants walked in five environments (Figure 1): (1) physical laboratory, with no VR (Physical-Lab); (2) virtual laboratory, with no visual obstructions or impediments (VR-Lab); (3) virtual doorway (VR-Door); (4) virtual hallway (VR-Hall); and (5) virtual street scene with crowds (VR-Crowd). The Physical-Lab was a 10 m x 17 m motion capture facility that served as a control condition for all VR environments. Coloured tape on the floor indicated the start and end of a 7 m walkway, and participants turned at the ends of the walkway. The VR-Lab was designed to simulate a similarly open and unobstructed space and served as a second control condition for the remaining VR environments. The VR-Door, VR-Hall, and VR-Crowd environments were selected and designed based on situations that have been shown to provoke FoG in people with PD [7]. Both the VR-Door and the VR-Hall were 1.62 m wide and 2.5 m high. The walls of the door and hall were made of a brick material and enclosed within the VR-Lab environment. The VR-Hall was 6 m in length, with turns completed within the virtual hall environment. The VR-Crowd environment was a street crossing 6 m long in an urban environment. Two avatars walked past the participant in the opposite direction, moving to avoid any collision with the participant. In all VR environments, changes in the walking surface indicated where to turn within the environment (different floor colour in VR-Lab, VR-Door, and VR-Hall; change from street to sidewalk in VR-Crowd).

Participants were first asked to walk through the Physical-Lab environment to ensure motion capture quality. After briefly gaining familiarity with VR through an acclimation environment consisting of a virtual living room, participants performed walking trials through the four VR environments in a randomized order. For all conditions, participants were asked to walk back and forth continuously for 1-2 30-s trials. Per environment, this protocol generated 6–8 walking passes through the motion capture volume and virtual environments, with an average of 20 usable steps per person per condition. Within practical constraints, this aligns with recommendations for a structured and rigorous approach to gait measurement in PD [27]. Participants wore a gait belt and were guarded by at least one licenced physical therapist. For VR trials, participants wore an HTC VIVE VR head-mounted display (HTC and Valve Corporation, New Taipei City, Taiwan) providing immersive 360-degree views of the virtual environment. The headset cables were managed by study staff to minimize contact with the participant and restriction of movement. All VR environments were created in Unity3D (Unity Technologies, San Francisco, CA, USA) using a combination of basic structures available in Unity and publicly available assets (Japanese Matsuri City, Zenrin Co., LTD, Fukuoka, Japan).

Gait analysis

During the walking trials, a 10-camera Qualisys Motion Capture System (Qualisys, Gothenburg, Sweden) recorded the three-dimensional position of markers and marker clusters placed bilaterally on the feet, legs, arms, pelvis, trunk, and head. Virtual environments were centred in the motion capture volume, and only straight walking was captured, with turns occurring outside the motion capture volume to minimize effects of acceleration and deceleration on measured variables. Visual3D (C-Motion, Inc., Rockville, MD, USA) was used to filter and process marker position data, build biomechanical models for each participant, and calculate gait outcomes. Steps were identified from position data of foot markers and confirmed *via* visual inspection. For each participant, gait outcomes were averaged across all steps available for a given condition to optimize the reliability and validity of spatio-temporal measures.

Gait outcomes were selected to represent independent domains of gait in PD [27]. This approach provided a conceptual underpinning for identifying different aspects of gait that could be impacted by VR among people with PD. The primary gait outcome was gait speed (m/s, pace domain), calculated as step length divided by step time. Secondary outcomes included one variable that loaded heavily on each of the five gait domains [27]: step length (m, pace domain), step time (s, rhythm domain), step length variability (m, variability domain, calculated as described in [28]), step time asymmetry (s, asymmetry domain), and step width (m, postural control domain). Only steady-state, straight-line walking was analyzed. Although FoG, with complete cessation of walking, was not observed in any environment, an analysis of festination, defined as excessive shortening of steps, was included because this phenomenon often precedes FoG [3]. Festination was calculated for each participant in each condition as the percentage of steps that were more than 3 standard deviations (SD) shorter than that participant's mean step length in the Physical-Lab condition. For normally distributed data in the Physical-Lab environment, it would be expected that approximately 0.15% of steps would meet this criteria. Higher values in other environments would reflect more frequent festination in that environment relative to the Physical-Lab environment.

At the end of each testing session, participants completed the Simulator Sickness Questionnaire (SSQ) [29] to assess any adverse effects from walking through the VR environments. This questionnaire has been employed to assess the use of immersive VR for people with PD [30]. Participants also responded to structured questions about their interest in seeing VR developed as a therapeutic tool and their interest in using such a VR intervention.

Statistical analysis

Descriptive analyses were used to characterize demographic and clinical characteristics (SPSS Statistics v19.0, Armonk, NY, USA). Potential differences in gait outcomes across conditions were

Table 1. Participant characteristics.

	Age (yrs)	Sex	PD Dur. (yrs)	LED (mg)	MoCA	ABC	Mini-BEST	NFoG	UPDRS, Part III	SSQ
PD-01	76	F	4.0	0	27	63	25	16	43	0
PD-02	68	M	4.0	900	25	66	22	8	67	22
PD-03	72	M	6.0	1600	26	38	24	16	39	37
PD-04	77	F	10.0	1596	27	76	21	13	34	45
PD-05	73	M	8.0	1200	29	62	22	11	36	34
PD-06	84	M	1.5	600	26	73	26	18	29	4
PD-07	83	M	1.0	550	18	52	15	10	54	7
PD-08	67	F	26.0	1514	26	77	27	13	53	4
PD-09	71	M	3.5	0	29	73	16	8	78	7
PD-10	70	M	14.0	1530	27	86	23	17	37	0
Mean (SD)	74.1 (5.9)	3 F, 7 M	7.8 (7.5)	949 (637)	26.0 (3.1)	66.4 (13.8)	22.1 (4.0)	13.0 (3.7)	47.0 (15.8)	16.1 (17.0)

ABC: Activities-Specific Balance Confidence Scale; Mini-BEST: Mini-Balance Evaluation Systems Test; LED: Levodopa Equivalent Daily Dose;[40] MoCA: Montreal Cognitive Assessment; NFoG: New Freezing of Gait Questionnaire: scored without video; PD Dur.: Durations since PD diagnosis; UPDRS, Part III: Movement Disorders Society Unified Parkinson Disease Rating Scale: Subscale III: Motor Examination; yrs: years.

assessed using a one-way repeated measures analysis of variance (ANOVA) with one within-subject factor (environment: Physical-Lab, VR-Lab, VR-Door, VR-Hall, VR-Crowd). Assumptions of normality and sphericity were met for all gait outcomes. There were two outliers in the step time data, as assessed by boxplot inspection. However, inspection of these data points determined they were valid and removal of these data points did not change ANOVA results, so they were retained in the final analysis. For ANOVAs, effect sizes were reported using partial eta squared (η_p^2). For significant ANOVAs ($\alpha = 0.05$), two simple contrasts were conducted. First, planned contrasts between the Physical-Lab and the four VR environments were used to determine if any gait variables were affected by immersive VR. Second, planned contrasts of the VR-Lab compared to the VR-Door, VR-Hall, and VR-Crowd were completed to determine whether VR environments based on FoG-provoking situations elicited changes in gait compared to an unobstructed VR laboratory environment. Because these were exploratory analyses, we used $\alpha = 0.05$ for all planned contrasts. For planned contrasts, mean difference, 95% confidence intervals (95% CI), and *p*-values are reported. All values below are mean (SD) unless otherwise noted.

Results

Of 25 potential participants who were screened, a total of ten people with PD were eligible and participated (Table 1). The duration of symptoms exceeded the duration of diagnosis for two participants (PD-06, PD-07), and two participants were not taking PD medications (PD-01, PD-09). For those participants taking PD medications, walking trials were completed an average of 197 (96) min after their most recent dose. One participant (PD-10) had bilateral subthalamic nucleus stimulators, which were on at the time of testing. Participants presented with evidence of cognitive impairment, based on MoCA scores, and moderate PD motor severity with Hoehn & Yahr stage ranging from 2–3. Balance and mobility deficits were evident in this sample, and five participants reported falls in the prior three months, with two participants experiencing a single fall and three participants experiencing recurrent falls. One participant (PD-04) required hand-held assist to complete the VR trials only, due to imbalance when walking in immersive VR.

The environments had statistically significant effects on gait speed, step length, step length variability, step width, and the frequency of festination (Table 2). The environment did not impact step time or step asymmetry (rhythm and asymmetry domains). Planned contrasts with the Physical-Lab environment demonstrated that immersive VR impacted several aspects of gait (Table 3). Gait speed was slower and step length was shorter for all VR environments compared to the Physical-Lab. Step length variability was greater only in the VR-Door and VR-Crowd environments compared to the Physical-Lab. Step width was greater in the VR-Lab, VR-Door, and VR-Hall environments compared to the Physical-Lab. Festination was more common only in the VR Door and VR-Crowd environments compared to the Physical-Lab. Planned contrasts with the VR-Lab environment demonstrated that step variability was greater in the VR-Door and VR-Crowd environments compared to the VR-Lab.

After the study, participants reported a range of simulator sickness scores, with mean values reflecting low levels of symptoms. When asked their perceptions of the VR experience, eight participants expressed interest in seeing this technology developed, and seven participants were interested in using VR as a therapeutic tool.

Discussion

This study assessed spatiotemporal gait changes during overground walking in immersive VR environments as an initial step in examining the potential utility of VR to study, assess, and treat FoG. The pace domain of walking was impacted by all VR environments, with slower gait speed and shorter steps compared to walking in a physical laboratory environment. Postural control was affected in some environments, with wider steps observed in the virtual laboratory, doorway, and hallway environments compared to the physical laboratory. Additional gait changes were observed only in virtual environments designed to replicate real-world situations that commonly provoke FoG – virtual doorways and crowds. Steps were more variable when walking in virtual doorway and crowd environments compared to the physical and the virtual laboratory environments. Similarly, festination was increased in virtual doorway and crowd environments compared to the physical laboratory. Because increased gait variability and festination are considered hallmarks of FoG and often precede FoG episodes [3,31], these changes may reflect more specific impacts of the VR simulations of FoG-provoking situations. Taken together, these results suggest that changes in pace and postural control domains of gait may reflect a more cautious walking pattern driven primarily by the use of immersive VR, while increases in variability and festination may result from the visuospatial aspects of VR environments designed to provoke FoG.

Virtual reality, whether immersive or non-immersive, has several strengths as a tool to understand, assess, and treat FoG. Non-immersive VR has been used to examine the neural substrates of FoG, implicating abnormal activation in and connectivity between cortical and subcortical regions [9–12]. In order to be compatible with neuroimaging, these studies typically use footpedals to

Table 2. Effect of physical and virtual environments on gait variables.

Variable	Phys-Lab	VR-Lab	VR-Door	VR-Hall	VR-Crowd	*F*	*p*	η_p^2
Pace domain								
Gait speed (m/s)	0.97 (0.20)	0.84 (0.25)*	0.80 (0.20)*	0.82 (0.18)*	0.84 (0.21)*	4.09	.008	.31
Step length (m)	0.54 (0.08)	0.48 (0.12)*	0.45 (0.10)*	0.46 (0.10)*	0.48 (0.08)*	6.92	<.001	.43
Rhythm domain								
Step time (s)	0.57 (0.08)	0.58 (0.08)	0.58 (0.08)	0.57 (0.05)	0.59 (0.08)	0.77	.55	.08
Variability domain								
Step length var. (m)	0.03 (0.01)	0.03 (0.01)	0.05 (0.02)*†	0.04 (0.01)	0.05 (0.02)*†	3.95	.009	.30
Asymmetry domain								
Step time asym. (s)	0.03 (0.02)	0.02 (0.02)	0.03 (0.02)	0.02 (0.02)	0.03 (0.02)	0.41	.80	.04
Postural control domain								
Step width (m)	0.13 (0.03)	0.14 (0.03)*	0.15 (0.03)*	0.14 (0.03)*	0.14 (0.03)	5.12	.002	.36
Festination								
% Steps	0.1 (0.4)	18.7 (29.6)	37.7 (29.0)*	21.3 (29.7)	20.4 (19.3)*	3.56	.02	.28

Values for each condition are mean (standard deviation). *F* (4, 36) values, *p*-values, and η_p^2 values are for one-way repeated measures ANOVA results. For planned contrasts, * indicates condition is significantly different from Physical-Lab condition ($p < .05$); † indicates condition is significantly different from VR-Lab condition ($p < .05$).

Table 3. Planned contrasts.

VR-Lab		VR-Door		VR-Hall		VR-Crowd	
Mean diff. (95% CI)	*p*	Mean diff. (95% CI)	*p*	Mean diff. (95% CI)	*p*	Mean diff. (95% CI)	*p*
Compared to Physical-Lab environment							
Gait speed (m/s)							
0.13 (0.04, 0.22)	.10	0.17 (0.11, 0.24)	<.001	0.16 (0.01, 0.30)	.04	0.14 (0.04, 0.23)	.009
Step length (m)							
0.06 (0.03, 0.09)	.003	0.09 (0.06, 0.12)	<.001	0.08 (0.03, 0.12)	.005	0.06 (0.03, 0.09)	.001
Step length variability (m)							
–		−0.02 (−0.03, 0.00)	.02	–		−0.02 (−0.04, 0.00)	.02
Step width (m)							
−0.01 (−0.02, 0.00)	.009	−0.02 (−0.03, −0.01)	.002	–		−0.01 (−0.02, 0.00)	.03
Festination (% Steps)							
–		−37.6 (−58.3, −16.8)	.003	–		−20.3 (−34.0, −6.6)	.009
Compared to VR-Lab environment							
Step length variability							
–		−0.02 (−0.03, −0.01)	.001	–		−0.02 (−0.04, 0.00)	.02

Significant results from planned contrasts, showing mean difference (95% CI) and *p*-values. Phys-Lab and VR-Lab were the reference conditions for all contrasts.

simulate walking in virtual environments that incorporate corridors and various types of doorways (wide, narrow, sliding glass), with freezing events defined using increased latency between footpedal steps. In the current study, virtual environments did not impact measures of the rhythm domain (measured here using step time, analogous to step latency), suggesting a potential difference in the changes elicited by non-ambulatory compared to ambulatory VR protocols for studying FoG. While non-ambulatory tasks are necessary for neuroimaging purposes, these do not have a spatial component related to step length and do not replicate the postural stability demands inherent in FoG. Future research should examine the utility of ambulatory VR applications for the clinical assessment and treatment of FoG, as ambulatory VR may have clinically relevant advantages over the non-ambulatory applications used to investigate the underlying mechanisms of FoG.

Emerging research is examining the utility of VR in the clinical assessment of FoG. The standard clinical tools for assessing FoG are self-reported measures, such as the NFoG Questionnaire [19], and observation during various tasks, including straight-line walking, gait initiation, or turning [32]. Specific environments, such as doorways, hallways, and crowds, commonly provoke FoG [3,7] and are used in both clinical [33] and experimental [34] assessments of FoG. However, it can be impractical and unsafe to physically replicate the various environments that provoke FoG in the clinic. Using VR, a wide variety of FoG-provoking environments can be standardized with predetermined difficulty levels. The absence of physical obstructions with VR also allows guarding against falls or the use of a safety harness. Though further research is needed, virtual environments appear to elicit gait changes that are similar to those observed with comparable physical environments. In the current study, people with PD walked more slowly, with shorter, wider, and more variable steps when walking through a virtual doorway compared to the physical laboratory. Similar gait changes have been demonstrated in people with PD when walking through variable-width physical [34] and virtual [17] doorways, suggesting the validity of virtual environments relative to their physical counterparts.

Given the potential safety advantages and extensive configuration and standardization options, VR also demonstrates potential as a treatment for FoG. Several studies have examined the use of VR to treat gait impairments, though not FoG specifically, among people with PD. A systematic review of randomized and quasi-randomized trials involving VR exercise interventions compared to standard physiotherapy for people with PD suggested the potential for moderate improvements in step and stride length with VR interventions [13]. More recently, VR combined with treadmill training was shown to reduce falls to a greater extent than treadmill training alone in people with PD, including those with and without FoG, despite the lack of measured benefits for FoG specifically [15,35]. Immersive VR during overground walking has also been used to improve gait symmetry in people with PD [16]. Additional research is needed to determine whether VR applications have specific utility in the treatment of FoG. Future studies could not only incorporate patient-specific FoG-provoking environments for task-specific practice, but could also incorporate

visual cues that can improve step length and ameliorate FoG, such as transverse lines [36] or staircase illusions [37].

In this study, we focussed on immersive VR and overground walking compared to previous VR research in PD involving non-immersive VR and either simulated walking or walking on a treadmill [13,14]. Some recent exceptions combine immersive VR and overground walking [16,17], a combination that may optimally replicate the demands of gait in everyday life for several reasons. First, immersive VR enables the virtual environment to be the only visual input available when the headset is being worn, providing visual effects like those experienced in everyday life including peripheral vision. Importantly, the current study and other recent research suggest that immersive VR is well-tolerated by people with PD [16,30]. A second advantage is that overground walking is possible with the use of immersive VR. Treadmill training is an unavoidable consequence of non-immersive VR since it requires a screen. However, treadmills constrain gait, requiring relatively constant gait speed without the ability to side-step or change directions. Immersive VR combined with overground walking provides immersive visual effects and allows for naturalistic movements like changing speed, turning, or avoiding obstacles, which are advantages for developing VR to assess and treat FoG in PD [9]. Future research could examine the utility of immersive VR combined with overground walking to study non-linear walking tasks that are known to provoke FoG, such as turning.

While VR has been of interest as a research platform, adopting this technology into clinics and homes as a rehabilitation tool remains a challenge. At this time, the integration of VR technology into clinical practice would likely require assistance and supervision by trained clinical personnel. Barriers to the clinical use of VR among people with PD include potential safety issues due to fall risk and barriers to usability because of cognitive impairment [38]. Although research demonstrates that people with PD can use immersive VR without adverse effects [30], individuals with vestibular dysfunction or people who experience motion sickness may not tolerate immersive VR. Future research should consistently monitor participant tolerance of VR. A related barrier is that many individuals have limited familiarity with VR. Future studies should consider how VR exposure impacts the response to the VR environments of interest, and optimal acclimation procedures should be determined. Because people with PD often report specific FoG-provoking situations or environments, a single, standardized environment may not be sufficiently patient-centred for clinical application. Future research can examine the utility of personalized VR applications compared to standardized applications. As VR technology advances, the flexibility, immersiveness, and realism will improve. While VR can always be improved to be more low-cost, portable, and immersive, the minimum technology to transfer research in VR and FoG into practice already exists.

Study limitations

This study was conducted with a small sample of individuals with PD who self-identified as having FoG yet could walk 400 m without assistance. Modifications to the eligibility criteria and experimental protocol may have increased the likelihood of freezing during the testing sessions. Individuals who walked with assistance from a device or another person were not eligible, excluding people with more substantial gait problems who may be more likely to freeze. In addition, study procedures were completed in the on-medication condition and only straight-line walking was assessed. It is estimated that over 60% of people with PD experience FoG only in the off-medication condition [8], and FoG is commonly experienced with turning [3]. Future studies could incorporate methodological changes to increase the likelihood of observed FoG episodes, like recruiting participants with more advanced PD, manipulating medication or deep-brain stimulation, or incorporating turns. Although differences in gait speed met published thresholds for meaningful change in people with PD [39], small sample size can negatively impact statistical power. Future research with larger samples is needed. A second limitation is that we did not compare the FoG-provoking environments tested in VR (doorway, hallway, crowd) with their physical counterparts to determine whether there was a difference in gait parameters when navigating such environments in VR versus real life. However, this study's findings are consistent with prior work demonstrating that people with PD walk more slowly, with shorter, wider, and more variable steps, when walking through physical [34] and virtual [17] doorways compared to an open laboratory environment. Together, these findings support doorways as a particularly provocative VR environment. A third limitation is that the acclimation time for the average participant was an unstructured 3-5 min exploration of a virtual home environment. Gait speed was slower and steps were shorter and wider in the VR-Lab compared to the Physical-Lab, suggesting that a more cautious gait pattern may have been driven by the novelty of walking in immersive VR. It is unclear whether the differences in gait between the Physical-Lab and VR-Lab environments would decrease with more structured practice walking in VR, as these participants had limited exposure to VR prior to the study. An additional impact of the VR environments designed to provoke FoG is suggested by the increased step variability in the virtual doorway and crowd environments compared to the virtual laboratory. Fourth, no comparison group was included, so it is unclear if the observed effects are specific to people with PD and FoG. Future work should include a control group of people with PD who do not experience FoG or of healthy older adults to examine the specificity of VR impacts in different populations. Lastly, there were no visual cues for where the feet were in the VR environment in contrast to recent work that incorporated visual feedback of the feet when walking in immersive VR [16,17]. This may have made walking more difficult in the VR environments, contributing to reduced gait speeds in all virtual environments.

Conclusion

This study demonstrates that pace and postural control aspects of gait were adversely impacted by the use of immersive VR, regardless of whether virtual environments contained visual elements designed to provoke FoG. In addition, virtual doorways and hallways resulted in increased step variability and festination compared to a physical laboratory and increased step variability compared to a virtual laboratory. These gait changes are identified as a precursors to FoG [3], suggesting that VR environments designed to provoke FoG may have additional impacts on gait. With rapidly advancing VR technology, future research is needed to understand the potential utility of ambulatory, immersive VR applications as a tool for the research and clinical management of FoG.

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