RESEARCH ARTICLE

Why Use Immersive Virtual Reality to Assess Gait in Functional Motor Disorders?

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ABSTRACT: Background: Functional motor disorders (FMD) are disabling conditions modulated by attentional demands. Immersive virtual reality (iVR) engages multiple attentional and sensory networks, but its application in people with FMD (PwFMD) remains limited.
Objective: We investigated whether iVR modulates spatiotemporal gait parameters in PwFMD differently from people with Parkinson's disease (PwPD) and healthy controls (HC).
Methods: Wearable insoles tracked spatiotemporal gait parameters in the PwFMD (n = 30), the PwPD (n = 32), and HCs (n = 42) across three real-world (C1–C3) and three iVR (C4–C6) walking conditions with increasing cognitive and sensory load. Discriminative performance was evaluated using receiver operating characteristic (ROC) analysis, whereas group and condition effects were examined using repeated-measures analysis of variance (ANOVA) adjusted for age, sex, and body mass index (BMI). The dual-task effect (DTE) quantified the impact of cognitive load.
Results: In the iVR condition (C4–C6), gait speed, stride length, and swing-time variability discriminated both PwFMD and PwPD from the HCs with good accuracy (AUC > 0.8), particularly under higher dual-task load (C5 and C6), whereas no parameter reliably differentiated the PwFMD from the PwPD using ROC analysis (AUC < 0.7). Adjusted ANOVA revealed significant group × condition interactions for multiple gait parameters ($P < 0.05$). DTE analysis revealed distinct responses to cognitive load: dual-task cost was greater in PwPD than in PwFMD, which was often comparable to the HCs, particularly under cognitive dual-task conditions (C3 and C6).
Conclusions: iVR revealed context-dependent gait abnormalities and differential responses to cognitive load in PwFMD and PwPD, which suggests its use as a paradigm to probe underlying mechanisms. © 2026 The Author(s). *Movement Disorders* published by Wiley Periodicals LLC on behalf of International Parkinson and Movement Disorder Society.

Key Words: dual task; functional motor disorders; gait analysis; immersive virtual reality; Parkinson's disease

Functional motor disorders (FMD) are among the most common presentations of functional neurological disorders (FND), in which motor symptoms (ie, weakness, tremor, dystonia, and gait disorders) are incongruent and inconsistent with recognized neurological diseases.[1-3] Diagnosis relies on positive rule-in signs (ie, entrainment in tremor and Hoover's sign in weakness) and on the demonstration of inconsistency and incongruity with recognized neurological diseases, including distractibility and suggestibility. Despite advances in

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clinical recognition, the absence of objective biomarkers continues to challenge the differential diagnosis of motor disorders from "organic" disorders.[4,5]

FND, and FMD by extension, are increasingly conceptualized within a predictive processing framework[3] that posits that perception and movement result from hierarchical interactions between top-down expectations and bottom-up sensory inputs. Functional symptoms are thought to emerge when maladaptive prior expectations acquire abnormal precision through attentional mechanisms and generate prediction errors that fail to be corrected.[6] These processes result in abnormal movement experiences and motor output.

Gait control depends on the continuous integration of motor, cognitive, and sensory processes.[7,8] In everyday life, walking often requires performing a secondary cognitive task that involves attentional and executive resources. In healthy individuals, it typically induces minor adaptive gait changes,[9] whereas in persons with neurological disorders such as Parkinson's disease (PD), it often leads to gait deterioration (slower gait and greater gait variability), with effects modulated by task complexity and cognitive capacity due to reduced automaticity and limited cognitive reserve.[9-11] In contrast, people with FMD (PwFMD) often show improvement when attention is redirected away from movement execution, likely due to reduced self-monitoring and a shift toward more automatic motor control.[12-15] However, exactly how different levels of attentional and cognitive load interact to reveal or mask functional gait abnormalities remains poorly understood. Developing diagnostic gait markers capable of differentiating between functional and organic disturbances could therefore enhance diagnostic accuracy and guide appropriate treatment (BEST—Biomarkers, Endpoints, and other tools Resource, Silver Spring, MD, 2016).[16]

Virtual reality (VR)–based paradigms have been successfully applied in neurological rehabilitation, particularly in PD, where immersive scenarios can enhance attentional engagement, replicate real-world challenges, and provide standardized task conditions.[17-19] In psychiatry, VR has been used in simulation and distraction therapy,[20] but research into VR applications in PwFMD is limited. Four studies have explored its potential so far: a mechanistic functional magnetic resonance imaging study that manipulated sense of agency through altered visuomotor synchrony,[21] a feasibility pilot randomized controlled trial that used VR mirror feedback,[22] a case report that employed three-dimensional (3D) motion tracking for physiotherapy,[23] and a case–control study that investigated VR-based modulation of postural control under graded attentional load.[13,24] Collectively, these findings suggest that VR may influence functional symptoms primarily through attentional mechanisms and offer a controlled framework with which sensory and cognitive demands can be manipulated during motor tasks.

Due to the interplay between cognitive and sensory factors in gait regulation, immersive VR (iVR) provides the means to explore how simultaneous modulation of these domains affects walking in different neurological conditions. By combining immersive visual and cognitive challenges within a controlled environment, iVR may enhance the detection of subtle gait disturbances otherwise not evident under standard real-world walking conditions. PD represents an ideal comparator for FMD, due to its characteristic gait deficits under dual-task conditions.[10]

In the present study we applied standardized dual-task gait assessment in both real-world and iVR settings to investigate whether iVR modulates spatiotemporal gait parameters differently in PwFMD, people with mild PD (PwPD), and healthy controls (HC). Our hypothesis was that iVR would enhance the detection of gait abnormalities among groups by inducing different context-dependent modulations of motor control, thus revealing differential responses to cognitive load across the three groups.

Patients and Methods

Study Design

For this cross-sectional observational study three groups were formed: 30 PwFMD[6] (mean age, 38.3 ± 13.8 years; 70% women), 32 PwPD (mean age, 65.4 ± 7.4 years; 34.4% women), and 42 HCs (mean age, 37.0 ± 15.8 years; 71.4% women). The subjects were consecutively recruited from the Neurology B Unit (AOUI Verona, Italy) between January and September 2024. FMD and PD diagnoses were made by the same movement disorders specialists (I.A.V and M.T.). FMD diagnoses were established by neurologists expert in movement disorders based on positive clinical signs demonstrating inconsistency and incongruity with the recognized neurological disease; the diagnoses were classified as "clinically established" according to Gupta and Lang's criteria.[6] None of the subjects had overlapping diagnoses.

Subjects

Inclusion criteria were age ≥18 years, Mini-Mental State Examination score >24/30, ability to maintain upright posture without assistive devices, and the absence of comorbidities affecting gait or balance. Exclusion criteria were psychiatric comorbidities based on medical records and patient history, peripheral neuropathies, vestibular disorders, and, for FMD, psychogenic nonepileptic seizures. FMD was defined by the presence of positive rule-in clinical signs and functional lower-limb motor or gait symptoms and rated using the

Simplified Functional Movement Disorders Rating Scale (S-FMDRS).[25] PwPD were included if the Hoehn and Yahr stage was ≤3, they were on stable dopaminergic therapy, and they did not have gait-interfering dyskinesias. Motor symptom severity was rated using the Movement Disorder Society-sponsored revision of the Unified Parkinson's Disease Rating Scale.[26] All subjects provided written informed consent. The study was approved by the local Ethics Committee (Prot. 3571CESC—JP-VR-19) and conducted in accordance with the Declaration of Helsinki.

Gait Assessment

Spatiotemporal gait parameters for real-time spatiotemporal gait analysis were recorded along a 15-meter walkway using FeetMe Smart Insoles (FeetMe, Paris, France), wearable devices equipped with 16 plantar pressure sensors, an accelerometer, and a gyroscope.[27] Gait domains were defined according to the established literature on dual-task sensitivity: (1) pace: gait speed (m/s) and stride length (m); (2) rhythm: step time (ms), stride time (ms), and double-support time (ms); and (3) variability: stride time variability (%) and swing-time variability (%).[9-11,13,15]

Immersive Virtual Reality Setting

Two immersive 3D environments were created (Khymeia, Padova, Italy) and displayed through an HTC Vive Pro Eye head-mounted display (HTC Corporation, New Taipei City, Taiwan) with integrated eye tracking (resolution 1440 × 1600 pixels per eye, a 110° diagonal field of view, and stereoscopic rendering powered by an Nvidia GeForce GTX 1060 graphics card). The system ensured free walking in a safe, infrared-tracked space. One environment replicated a hospital corridor and matched the real-world walkway in dimensions and appearance (ie, colors), thereby generating a low sensory and attentional load, whereas the other simulated a realistic city-like environment with static (trees, sidewalks) and dynamic (pedestrians walking at variable speeds) elements and environmental sounds for increased realism.[28] In both scenarios, a red fixation cross was positioned centrally to guide attention.

Study Protocol

In all there were six walking conditions in which sensory and cognitive loads were manipulated in real-world and iVR settings (Fig. 1). The subjects were told they could walk at a self-selected comfortable speed. They were familiarized with each iVR condition for 10 sec. Real-world conditions were as follows: C1, single-task walking; C2, visual fixation dual task (fixating a red cross at the end of the corridor); and C3, cognitive dual task (serial subtraction by 7 from 200). iVR conditions were as follows: C4, visual fixation dual task in a city-like environment (ignoring moving pedestrians); C5, visual fixation dual task in a virtual hospital corridor; and C6, cognitive dual task in a city-like environment (counting the moving pedestrians).

Each trial began with C1, after which the other conditions (C2–C6) were randomized. Dual-task instructions were given in standardized verbal cues.

Statistical Analysis

Descriptive statistics were performed to determine frequency distributions for categorical variables and means (standard deviation [SD]) for continuous variables. One-way analysis of variance (ANOVA) and

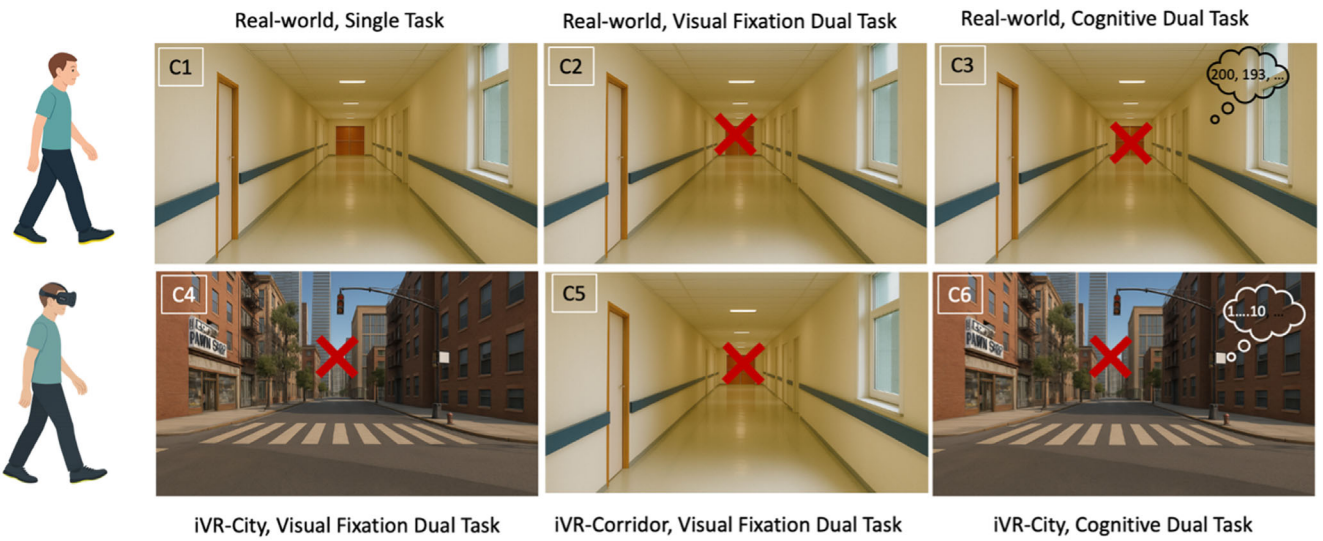

FIG. 1. Overview of experimental walking conditions. C, condition. Condition C1 was always administered first; the order of C2–C6 was randomized. [Color figure can be viewed at wileyonlinelibrary.com]

Bonferroni's post hoc tests were performed to determine differences in age and body mass index (BMI) between the three groups; χ^2 test was applied to determine association with sex. Receiver operating characteristic analysis was used to evaluate the discriminative ability of spatiotemporal gait parameters between groups (PwFMD vs. HC, PwFMD vs. PwPD, and HC vs. PwPD) across conditions. The area under the curve (AUC) was interpreted as excellent (0.9–1.0), good (0.8–0.9), moderate (0.7–0.8), poor (0.6–0.7), and insufficient (0.5–0.6). Repeated-measures ANOVA with Bonferroni's post hoc tests (adjusted for the covariates age, sex, BMI) was applied to evaluate differences in gait parameters across the three groups (HC, PwFMD, PwPD) and the six conditions (C1–C6). The assumption of sphericity was verified using Mauchly's test; if violated ($P < 0.05$), Greenhouse–Geisser corrections were applied. All tests were bilateral with statistical significance set at $P < 0.05$. Normality was verified using Shapiro–Wilk test. Additional analyses were performed to explore group-specific changes in performance under different cognitive load conditions (C2–C6) compared with C1. The dual-task effect (DTE) was calculated for each spatiotemporal gait parameter and for each subject. The DTE was defined as follows:

$$\mathrm{DTE} = \frac{\text{single task} - \text{dual task}}{\text{single task}} \times 100$$

where single-task performance corresponded to C1 performance and dual-task performance corresponded to each dual-task condition (C2–C6).[29] Positive and negative DTE values reflected the direction of change relative to single task. DTE values were compared across groups (HC, PwFMD, PwPD) using one-way analysis of variance (ANOVA). Post hoc comparisons were performed using Bonferroni's correction, when applicable. All tests were bilateral with statistical significance set at $P < 0.05$. Normality was verified using Shapiro–Wilk test. Statistical analyses were performed using IBM SPSS Statistics, version 29.0.

Results

Study Sample Characteristics

Significant group differences were found for age ($P < 0.001$), gender distribution ($P = 0.002$), and BMI ($P = 0.009$). The PwPD group was older and had a higher BMI and a higher proportion of men. Table 1 and Table S1 present the descriptive sample characteristics.

TABLE 1 Demographic and clinical characteristics

	HC (n = 42)	PwFMD (n = 30)	PwPD (n = 32)	*P*-value	Bonferroni's post hoc
Age (yr), mean ± SD	37.0 ± 15.8	38.3 ± 13.8	65.4 ± 7.4	<0.001[a]	$P < 0.001$ HC<PwPD $P < 0.001$ FMD<PwPD
Women, number (%)	30 (71.4)	21 (70.0)	11 (34.4)	0.002[b]	
BMI, mean ± SD	23.3 ± 3.7	23.5 ± 4.7	26.1 ± 3.9	0.009[a]	$P = 0.011$ HC<PwPD $P = 0.036$ PwFMD<PwPD
S-FMDRS, mean ± SD					
Lower-limb severity		1.42 ± 1.09			
Lower-limb duration		1.50 ± 1.11			
Gait severity		0.93 ± 1.03			
Gait duration		1.33 ± 1.32			
Disease duration (yr), mean ± SD			6.9 ± 4.7		
H&Y ON, mean ± SD			2.13 ± 0.49		
MDS-UPRDS, mean ± SD			48.38 ± 15.88		
MDS-UPDRS III, mean ± SD			26.47 ± 10.90		
LEDD, mean ± SD			640.22 ± 343.90		
MOCA, mean ± SD			26.41 ± 2.50		

Abbreviations: HC, healthy controls; PwFMD, people with functional motor disorders; PwPD, people with Parkinson's disease; SD, standard deviation; BMI, body mass index; S-FMDRS, Simplified Functional Movement Disorders Rating Scale; H&Y, Hoehn and Yahr; MDS-UPDRS, Movement Disorder Society-sponsored revision of the Unified Parkinson's Disease Rating Scale; LEDD, levodopa equivalent daily dose; MOCA, Montreal Cognitive Assessment; ON, ON medication state.
[a]One-way analysis of variance.
[b]χ^2 test.

Discriminatory Performance by Condition

In C2 (real-world visual fixation dual task), stride length discriminated the PwFMD from the HCs and the PwPD from the HC with good accuracy (AUC >0.8). In C5 (iVR visual fixation dual task), gait speed, stride length, and swing-time variability differentiated the PwFMD from the HCs (all AUC >0.8).

Of all gait parameters, swing-time variability had the most consistent discriminative performance across the six iVR conditions. It was the only parameter to demonstrate both significant group × condition interaction effects and good discriminative accuracy (AUC >0.8) in distinguishing the PwFMD and the PwPD from the HCs under high cognitive and sensory load conditions (C6). No gait parameter discriminated the PwFMD from the PwPD in any condition (AUC <0.8). Figure 2 shows the AUC for discriminating the performance of spatiotemporal gait parameters across the real-world and iVR conditions. Table S2 (comparison between and within groups across conditions for spatiotemporal gait parameters) presents the mean and SD of spatiotemporal gait parameters.

Main Effects

Between-group effects (if the three groups differed overall) and within-group effects (if some of the six conditions differed from others) were examined using repeated-measures ANOVA adjusted for age, BMI, and sex. Because the assumption of sphericity was violated for all parameters, Greenhouse–Geisser correction was applied. Both between- and within-group effects were significant at $P < 0.05$ for all pace gait parameters (Table 2), for the rhythm and phase gait parameters (Table 3), and for the swing-time variability (Table 4).

The PwFMD walked more slowly, with shorter strides, longer steps, greater double-support times, stride and swing times, and greater swing-time variability than the HCs. The PwFMD walked slower than the PwPD but took longer steps and longer stride and swing times. The PwPD took shorter strides than the HCs. Gait speed and stride length decreased, whereas step time, double-support time, stride time, swing time, and swing-time variability increased with higher sensory and cognitive load (C3–C6 vs. C1–C2). Although these differences reached statistical significance, their clinical discriminative value remained limited, with AUC values ranging from poor to moderate (Fig. 2).

Group × Condition Interaction Effects

To explore whether the groups differed across conditions, the group × condition interaction for each gait parameter was estimated using repeated-measures ANOVA, adjusted for age, BMI, and sex. Among the pace gait parameters, gait speed ($P = 0.013$), stride length ($P = 0.004$), and double-support time ($P = 0.022$) were statistically significant. Bonferroni's post hoc tests were applied to determine how the three groups behaved differently across conditions. In all conditions (except C3) the PwFMD walked slower than the HCs. The stride length was shorter for the PwFMDs than the HCs in all conditions. The PwPD performed worse than the HCs in C2, C3, and C6. The double-support time was longer for the PwFMD than the HCs in C4 and C5. Swing-time variability was higher for the PwFMD in C1, C4, C5, and C6. Figure S1 reports post hoc results adjusted for age, BMI, and sex for changes in spatiotemporal gait parameters across conditions (Tables S3, S4 and S5). Exploratory analysis comparing the spatiotemporal gait parameters in the PwFMD presenting baseline clinical gait abnormalities (n = 20) and in those without clinically evident gait impairments (n = 10) found no statistically significant between-group differences, group × condition interactions, or DTE differences (Tables S6 and S7).

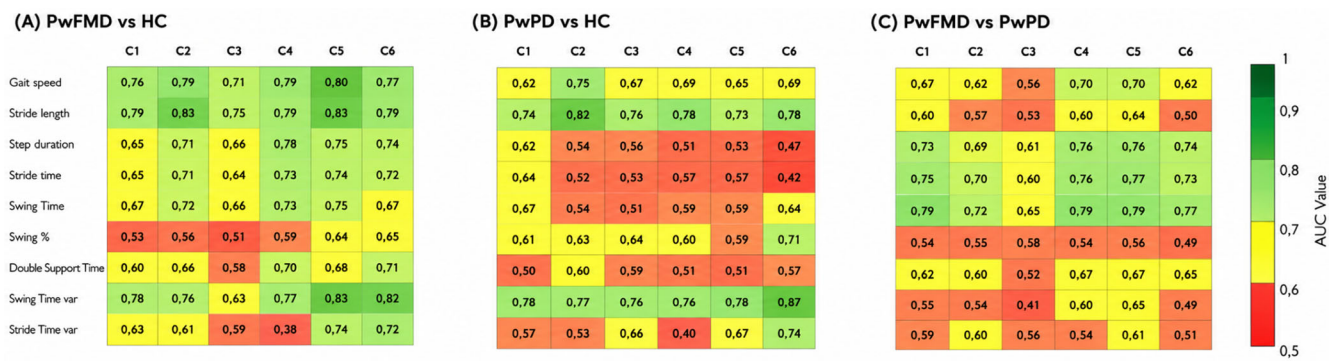

FIG. 2. Discriminative performance of spatiotemporal gait parameters across real-world and immersive virtual reality conditions. AUC (area under the curve) was considered as follows: 0.9–1.0: excellent, 0.8–0.9: good, 0.7–0.8: moderate, 0.6–0.7: poor, 0.5–0.6: insufficient. C1, single-task in the real-world corridor; C3, cognitive dual task in the real-world corridor; C4, visual fixation dual task in iVR (immersive virtual reality); C5, single-task walking iVR; C6, cognitive dual task in iVR; FMD, people with functional motor disorders; HC, healthy control; PD, people with Parkinson's disease. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Pace gait parameters: repeated-measures ANOVA for three groups (HC, PwFMD, PwPD) and six conditions adjusted for age, BMI, and sex

	Pace gait parameters							
	Gait speed		Stride length		Step time		Double-support time	
	Effect (*P*-value)	Effect size (partial η^2)	Effect (*P*-value)	Effect size (partial η^2)	Effect (*P*-value)	Effect size (partial η^2)	Effect (*P*-value)	Effect size (partial η^2)
Between-group effects								
Groups	<0.001	0.204	<0.001	0.257	<0.001	0.153	0.003	0.119
Within-group effects								
Conditions	<0.001	0.446	<0.001	0.414	<0.001	0.193	<0.001	0.212
Interaction effects								
Groups × conditions	0.0013	0.053	0.004	0.062	0.115	0.039	0.022	0.054

Bonferroni's post hoc test for interaction effects ($P < 0.05$)	**Groups**	**Mean difference (SE) *P*-value**	**Groups**	**Mean difference (SE) *P*-value**	**Groups**	**Mean difference (SE) *P*-value**	**Groups**	**Mean difference (SE) *P*-value**
C1	HC>PwFMD	0.23 (0.05) $P = 0.007$	HC > PwFMD	0.19 (0.04) $P < 0.001$	–	–	–	–
C2	HC>PwFMD	0.29 (0.05) $P < 0.001$	HC > PwFMD HC>PwPD	0.22 (0.04) $P < 0.001$ 0.15 (0.04) $P = 0.045$	–	–	–	–
C3	–	–	HC>PwFMD HC>PwPD	0.18 (0.04) $P = 0.017$ 0.18 (0.05) $P = 0.037$	–	–	–	–
C4	HC>PwFMD	0.28 (0.06) $P < 0.001$	HC>PwFMD	0.22 (0.04) $P < 0.001$	–	–	HC<PwFMD	−93.01 (24.87), $P = 0.050$
C5	HC > PwFMD	0.30 (0.06) $P < 0.001$	HC>PwFMD	0.25 (0.04) $P < 0.001$	–	–	HC<PwFMD	−91.54 (24.43), $P = 0.048$
C6	HC > PwFMD	0.24 (0.06) $P = 0.014$	HC>PwFMD HC>PwPD	0.21 (0.05) $P = 0.003$ 0.20 (0.05) $P = 0.007$	–	–	–	–

Notes: C1, single-task walking; C2, visual fixation dual task; C3, cognitive dual task; C4, visual fixation dual task in a city-like environment, ignoring moving pedestrians; C5, visual fixation dual task in a virtual hospital corridor; C6, cognitive dual task in a city-like environment, counting the number of moving pedestrians. C1–C3 indicate real-world conditions, and C4–C6 indicate immersive virtual reality conditions.
Abbreviations: ANOVA, analysis of variance; HC, healthy control; PwFMD, people with functional motor disorders; PwPD, people with Parkinson's disease; BMI, body mass index; SE, standard error of the mean.

TABLE 3 Rhythm and phase gait parameters: repeated-measures ANOVA for three groups (HC, PwFMD, PwPD) and six conditions adjusted for age, BMI, and sex

	Rhythm and phase gait parameters			
	Stride time		Swing time	
	Effect (*P*-value)	Effect size (partial η^2)	Effect (*P*-value)	Effect size (partial η^2)
Between-group effects				
Groups	0.002	0.130	<0.001	0.143
Within-group effects				
Conditions	<0.001	0.150	<0.001	0.228
Interaction effects				
Groups × conditions	0.428	0.021	0.544	0.017
Bonferroni's post hoc test for interaction effects ($P < 0.05$)	**Groups**	**Mean difference (SE) *P*-value**	**Groups**	**Mean difference (SE) *P*-value**
C1	–	–	–	–
C2	–	–	–	–
C3	–	–	–	–
C4	–	–	–	–
C5	–	–	–	–
C6	–	–	–	–

Notes: C1, single-task walking; C2, visual fixation dual task; C3, cognitive dual task; C4, visual fixation dual task in a city-like environment, ignoring moving pedestrians; C5, visual fixation dual task in a virtual hospital corridor; C6, cognitive dual task in a city-like environment, counting the number of moving pedestrians. C1–C3 indicate real-world conditions, and C4–C6 indicate immersive virtual reality conditions.
Abbreviations: ANOVA, analysis of variance; HC, healthy control; PwFMD, people with functional motor disorders; PwPD, people with Parkinson's disease; BMI, body mass index; SE, standard error of the mean.

DTE Analysis

Table S8 presents the results of DTE analysis.

Between-Group Effects (by Condition)

DTE revealed significant between-group differences across conditions. Under cognitive dual-task conditions, the dual-task cost was greater for the PwPD than for either the HCs or the PwFMD for gait speed and stride length in both the real-world cognitive condition (C3) and the iVR cognitive condition (C6), with additional differences between the PwPD and the PwFMD observed for stride length in C6. In the real-world visual fixation condition (C2), the dual-task cost was greater for the PwPD than for the HCs across pace and temporal parameters, whereas the cost was greater for both the PwPD and the PwFMD than the HCs for step and stride time.

Across-Condition Patterns of DTE

DTE varied across conditions. Deterioration in cognitive dual-task conditions (C3 and C6) was consistently greater for the PwPD than for the HCs and the PwFMD, whereas the dual-task cost was lower for the PwFMD. In contrast, in iVR visual fixation conditions (C4 and C5), the dual-task cost was greater for the PwFMD than the HCs across spatiotemporal gait parameters and was more evident in C5.

Discussion

Our study provides novel evidence that iVR enhances the detection of gait abnormalities in PwFMD and has potential diagnostic utility. By systematically manipulating attentional and sensory demands across real-world and iVR conditions, we found that spatiotemporal gait alterations in the PwFMD are highly context dependent and become most pronounced under complex iVR dual-task conditions. Swing-time variability emerged as a promising digital biomarker of altered motor automaticity in the PwFMD under iVR, whereas stride length and gait speed reflected more general differences in gait performance across the three groups. The absence of between-group differences during single-task real-world walking further supports our interpretation that group-specific gait abnormalities are not baseline features but rather context-dependent

TABLE 4 Variability gait parameters: repeated-measures ANOVA for three groups (HC, PwFMD, PwPD) and six conditions adjusted for age, BMI, and sex

	Variability gait parameters			
	Stride time		Swing time	
	Effect (*P*-value)	Effect size (partial η^2)	Effect (*P*-value)	Effect size (partial η^2)
Between-group effects				
Groups	0.720	0.007	<0.001	0.168
Within-group effects				
Conditions	0.207	0.017	<0.001	0.084
Interaction effects				
Groups × conditions	0.321	0.025	0.014	0.053
Bonferroni's post hoc test for interaction effects ($P < 0.05$)	**Groups**	**Mean difference (SE) *P*-value**	**Groups**	**Mean difference (SE) *P*-value**
C1	–	–	HC<PwFMD	−6.64 (1.64) $P = 0.016$
C2	–	–	–	–
C3	–	–	–	–
C4	–	–	HC<PwFMD	−6.32 (1.65) $P = 0.035$
C5	–	–	HC<PwFMD	−8.02 (1.61) $P < 0.001$
C6	–	–	HC<PwFMD	−5.73 (1.39) $P = 0.012$

Notes: C1, single-task walking; C2, visual fixation dual task; C3, cognitive dual task; C4, visual fixation dual task in a city-like environment, ignoring moving pedestrians; C5, visual fixation dual task in a virtual hospital corridor; C6, cognitive dual task in a city-like environment, counting the number of moving pedestrians. C1–C3 indicate real-world conditions, and C4–C6 indicate immersive virtual reality conditions.

Abbreviations: ANOVA, analysis of variance; HC, healthy control; PwFMD, people with functional motor disorders; PwPD, people with Parkinson's disease; BMI, body mass index; SE, standard error of the mean.

phenomena that manifest when attentional and sensory demands are increased in iVR contexts. Consistently, no between-group differences were observed in the real-world cognitive dual-task condition (C3). This indicates that increased cognitive load alone may be insufficient to elicit disorder-specific gait patterns in the absence of immersive sensory modulation. Taken together, these findings suggest that real-world dual-task paradigms may be less sensitive than iVR dual-task conditions in discriminating between functional and organic gait patterns, which supports the added value of iVR as a context-sensitive tool for revealing disorder-specific gait abnormalities. However, additional differences emerged when response to task demands was considered. DTE) analysis revealed that the dual-task cost was high for the PwPD and low for the PwFMD, which was often comparable to HCs, particularly under cognitive dual-task conditions. These findings indicate that, although the PwFMD and the PwPD may appear similar on static gait measures, they differ in their response to cognitive load. Overall, these results suggest that group differences are more effectively captured by the response to cognitive load than by absolute gait performance, as measured by the DTE. Future studies should assess its diagnostic accuracy in independent cohorts and determine whether it provides incremental value beyond conventional gait metrics.

Our findings are consistent with a progressive increase in attentional redirection across experimental conditions. The real-world visual dual-task condition (C2) placed a modest attentional burden without substantial cognitive demands and revealed early signs of attentional interference. Particularly, only the PwFMD had reduced gait speed compared with single-task walking, which suggests greater sensitivity to attentional manipulation. However, the relatively small condition-specific effects indicate that real-world visual dual tasking alone is insufficient to uncover disorder-specific gait abnormalities. As cognitive and sensory demands increased in the iVR dual-task conditions, the effects of

attentional redirection became more nuanced. Under cognitive dual tasking, the dual-task cost was lower for the PwFMD than for the PwPD. Moreover, the iVR introduced additional sensory and contextual demands that are unlikely to be explained only by attentional diversion. Rather, our findings suggest that gait performance emerges from an interaction between attentional allocation, sensory processing, and environmental complexity and results in context-dependent motor responses. This pattern supports a graded influence of cognitive and sensory load on gait modulation. In contrast, gait impairment in the PwPD is more likely driven by deficits in internal cueing and bradykinesia associated with basal ganglia dysfunction.[7,10] Overall, the iVR protocol was well tolerated and did not compromise task execution or participant safety.

Taken together, our results indicate that the effects of dual tasking in the PwFMD cannot be due to a simple deterioration or normalization of gait performance. Instead, they may reflect dynamic interactions between attentional and sensory mechanisms. These observations can be interpreted within the predictive processing framework of FMD.[3,5] According to this model, abnormal top-down predictions are assigned excessive precision, whereas bodily sensations acquire disproportionate salience and direct excessive attention to the body and its functions. Such processes may reinforce maladaptive prior beliefs and contribute to the misinterpretation of physical sensations.[13] Conversely, redirecting attention away from movement may reduce maladaptive top-down control and facilitate more automatic motor behavior. Further research is needed to determine how attentional redirection and sensory contextual factors interact within predictive processing models of FMD.

Our findings align with previous evidence that dual-task paradigms increase gait dysfunction in neurological populations[7,9] and that attention redirection can transiently normalize movement in PwFMD under moderate load.[13,15] Our results extend this concept by showing that immersive environments integrating both sensory and cognitive challenges further strengthen the ability to probe differences between functional and organic gait patterns. Previous feasibility studies using nonimmersive VR showed acceptability and engagement in PwFMD[22,23] but lacked quantitative gait measures. The present study adds novel evidence that swing-time variability in immersive dual-task settings has superior sensitivity in differentiating the PwFMD from the HCs, thereby making it a new digital marker of functional gait disturbances otherwise not detectable in real-world conditions.[13,15] Indeed, among all gait parameters, swing-time variability exhibited the most consistent discriminative performance across immersive conditions, with AUC >0.8 in both PwFMD versus HC and PwPD versus HC comparisons.

Clinically, these findings support the concept of iVR as a potential diagnostic "stress test" for functional gait disturbances. By concurrently influencing sensory and cognitive systems, iVR reveals context-dependent motor inconsistencies, such as increased swing-time variability, that are often hidden in standard real-world assessments. This feature aligns with FMD diagnostic criteria, where inconsistency and incongruence are crucial rule-in signs.[1,3] A key clinical strength of the protocol is its graded manipulation of attentional and cognitive demands, which enables individualized gait assessment and stepwise dual-task exposure within a patient-centered framework that complements real-world evaluation and informs rehabilitation.

Furthermore, the modulation of gait patterns observed in the PwPD under iVR conditions highlights its potential therapeutic relevance, particularly in structured immersive contexts, without implying a generalized improvement across task conditions.[30] Structured and predictable visual environments may provide external cues that partially compensate for impaired internal timing mechanisms, which is consistent with cueing-based rehabilitation approaches.[31] Therefore, iVR may hold a dual advantage: for diagnosis by enhancing the differentiation between functional and organic gait patterns, and for therapy by enabling tailored interventions that target disorder-specific mechanisms, excessive self-monitoring in PwFMD, and external cueing strategies in PwPD.

From a translational standpoint, integrating iVR with wearable sensor analysis lays the foundation for developing digital biomarkers in movement disorders. Swing-time variability during immersive dual-task walking reflects instability of automatic gait control and emerges as a distinguishing FMD from both PwPD and HCs. Moreover, the observed changes in swing-time variability should not be interpreted as normalization of gait. Rather, the attenuation of differences between the PwFMD and the HCs under conditions of attentional redirection (C2 and C3) might reflect a context-dependent inconsistency of motor control, whereby gait variability fluctuates according to cognitive demands. In this context, iVR should be interpreted as a paradigm to probe disorder-specific mechanisms of gait control rather than as a stand-alone diagnostic biomarker or rehabilitation tool. The heterogeneity of FMD may limit the identification of a single robust biomarker; instead, it suggests that context-dependent measures of motor control may better capture disorder-specific features across different clinical phenotypes. Future studies with larger samples will be needed to explore whether specific FMD subtypes exhibit distinct responses to iVR and dual-task paradigms, which may further refine the potential of these measures as biomarkers. Indeed, several methodological strengths of the present study support these results. The use of

wearable insoles enabled natural gait evaluation without constraining movement or requiring laboratory instrumentation. The inclusion of six conditions allowed for precise examination of cognitive and sensory load effects. Task order randomization minimized adaptation bias, and standardized instructions ensured reproducibility.

Nonetheless, several limitations must be acknowledged. The PwPD group was older than the PwFMD and the HC groups, which may have influenced variability parameters despite statistical control. All the PwPD were assessed in the *on* medication state, which may have mitigated deficits and blurred group contrasts. Future studies should compare *on* and *off* medication states and include other neurological gait disorders, such as cerebellar ataxia, to better define the specificity of iVR gait markers. Finally, only lower-limb spatiotemporal metrics were analyzed; future work integrating postural, kinematic, and neurophysiological measures could yield deeper insight into motor regulation in immersive contexts. Also, future studies should explore whether differences in modulation of gait exist in iVR conditions between PwFMD with and without overt clinical gait abnormalities.

In conclusion, iVR revealed context-dependent gait alterations in the PwFMD and distinct responses to cognitive load in the PwPD. These findings shed light on the role of attentional and sensory modulation in motor control and support the use of iVR as a paradigm to probe disorder-specific mechanisms in PwFMD. ●

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A.S.: 2A, 2B, 2C, 3A
G.B.: 1C, 3B
I.A.V.: 1C, 3B
L.A.: 1B, 3B
E.P.: 1B, 3B
M.C.: 1C, 3B
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M.P.: 1C, 3B
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Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Supporting Data

Additional Supporting Information may be found in the online version of this article at the publisher's web-site.