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Research Article

Walking in virtual reality: Effects on gait biomechanics and the role of speed

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HIGHLIGHTS

- VR alters gait biomechanics primarily through speed-related changes.
- Gait speed drives joint angle differences in VR vs. real-world walking.
- Covariation speed unveils VR's true biomechanical impact on gait.
- Joint kinematics in VR align with real world when speed is controlled.

ABBREVIATIONS

HMD	Head-mounted display
RLab	Real-world laboratory
SPM	Statistical parametric mapping
VR	Virtual reality
VRLab	Virtual laboratory

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BACKGROUND: Virtual reality (VR) has gained attention for its potential in gait rehabilitation, offering innovative approaches to improving motor recovery and functional mobility. The impact of VR environments on gait biomechanics remains unclear. Conflicting findings in the literature highlight the need to control for gait speed, a known factor influencing joint kinematics and spatiotemporal parameters.
AIM: This study aimed to determine whether VR environments alter lower limb joint angles during overground walking and to what extent these effects are influenced by gait speed.
METHODS: Twenty-one healthy participants walked in real-world (RLab) and virtual (VRLab) laboratories at a self-selected speed. Joint angles were analyzed using statistical parametric mapping (SPM) with and without covarying for dimensionless gait speed. A repeated measures ANOVA was used to compare joint angles between conditions.
RESULTS: Participants walked slower in VRLab compared to RLab. Significant differences in pelvic, hip, knee, and ankle joint angles were observed across the gait cycle without accounting for speed. However, no significant differences in joint angles were found between the two environments after covarying for gait speed.
INTERPRETATION: These findings suggest that the differences in joint angles during VR walking are primarily attributable to slower walking speeds rather than the VR environment. This highlights the importance of controlling for gait speed in VR gait analysis to avoid confounding effects and misinterpretation. These results support VR's feasibility in gait research and rehabilitation when appropriately controlled for speed.

KEYWORDS: Motor Control | Gait | Joint angles | Kinematics

INTRODUCTION

Virtual Reality (VR) is a computer-generated simulation of a three-dimensional environment that can replace natural sensory inputs with artificial visual, auditory, and haptic stimuli. VR in health-related applications has rapidly expanded due to its capacity to enhance engagement, motivation, and enjoyment during physical rehabilitation, reducing the perception of pain and discomfort [1]. Recently, VR has attracted growing interest in gait rehabilitation, offering promising avenues to enhance motor recovery and functional mobility through immersive, task-specific environments [2,3].

Despite these advantages, walking in VR can induce notable changes in gait mechanics, which must be carefully accounted for when evaluating motor function. Studies have reported mixed findings on how VR affects spatiotemporal gait parameters and joint kinematics. For instance, Horsak et al. [4] and Martelli et al. [5] observed reduced walking speed and alterations in lower limb joint angles when participants walked in VR compared to real-world (RW) settings. Similarly, Chan et al. [6] reported significant differences in stride length, cadence, and center of pressure stability during treadmill walking with head-mounted VR devices, while joint kinematics remained largely unaffected.

Understanding these differences is crucial because walking speed is a significant determinant of gait kinematics and kinetics. In a systematic review and meta-analysis, Fukuchi et al. [7] demonstrated that walking speed variations significantly affect spatiotemporal parameters, joint angles, and ground reaction forces. Lu et al. [8] also emphasized the influence of walking speed on balance control, showing that preferred walking speed optimizes the dynamic relationship between the body's center of mass and center of pressure. Ziegler et al. [9] reinforced the central role of gait speed in shaping stride duration and frequency, further highlighting the importance of controlling for speed when comparing gait across different conditions.

Moreover, the ecological validity of VR-based assessments depends on the fidelity with which VR walking replicates natural gait. Studies using overground walking and omnidirectional treadmills have shown that users often adopt more conservative gait strategies in VR [10], characterized by slower speeds, shorter steps, and increased variability—possibly due to visual-vestibular mismatches and unfamiliarity with the virtual environment [11,12].

Given the variability in previous findings, it remains unclear whether VR directly alters joint kinematics or whether observed differences are primarily due to changes in walking speed. To address this gap, the present study evaluates lower limb joint angles during overground walking in both VR and real-world conditions, focusing on controlling for gait speed. By analyzing joint kinematics under matched speed conditions, we aim to isolate the specific influence of VR on lower limb biomechanics. We hypothesize that when walking speed is controlled, there will be no significant differences in joint angles between VR and real-world walking conditions, suggesting that previously observed discrepancies are predominantly driven by speed-related adaptations rather than by VR exposure per se.

METHODS

The study utilized a dataset [13] involving 21 healthy participants (9 males, age: 37.62 ± 8.55 years) to examine gait biomechanics in real and virtual environments, based on the following inclusion criteria: age between 21 and 56 years and absence of temporary or chronic conditions that could impair walking (e.g., musculoskeletal injuries, neurological disorders, vestibular dysfunction). These criteria were verified through a screening conducted by a physiotherapist. There were no specific restrictions regarding BMI or physical activity level; participants displayed various anthropometric profiles (weight: 54–109 kg; height: 158–186 cm).

Prior experience with virtual reality was not required: four participants had never used a head-mounted display (HMD), and the remainder had minimal previous exposure (one or two times). Participants walked at self-selected speeds across experimental conditions: a real laboratory (RLab) and a virtual laboratory resembling the real world (VRLab, 11.9 × 5.4 m). The virtual environment was designed to match the real laboratory in spatial dimensions and general structure, including the same room proportions and walkway length. However, the VRLab contained simplified visuals: surfaces were rendered with uniform colors rather than photorealistic textures and ambient and static lighting. No ambient sounds were played during the VR condition. These choices were made to reduce visual complexity and avoid inducing cybersickness, while preserving ecological validity for walking-related tasks. The order of conditions was randomized across participants to minimize potential order effects such as practice, fatigue, or task familiarization. Data were collected using a 12-camera motion capture system and a force plate. The motion capture system recorded marker trajectories at a sampling frequency of 150 Hz. Ground reaction forces were acquired via a synchronized force plate (Kistler) operating at 900 Hz. Participants received the VR experience using a wirelessly operated head-mounted display (HMD, HTC, Vive Pro). The HMD featured a resolution of 1440 × 1600 pixels per eye (2880 × 1600 combined) and operated at a refresh rate of 90 Hz, providing smooth visual feedback and minimizing motion blur. A calibration procedure was performed to ensure spatial alignment between the real and virtual environments. The VRLab was manually aligned to the dimensions and orientation of the physical laboratory using Unity3D. Five HTC Vive Lighthouses (2.0) were installed to track the HMD and foot-mounted trackers.

Before each experimental trial, participants stood in a neutral posture to perform a calibration trial, which was used to align head orientation and correct for any drift or offset in the virtual rendering. This ensured the virtual walkway matched the physical one in position and scale. Participants walked along a 7-meter straight walkway, performing turns at its ends (not analyzed). The walkway was centrally aligned along the longitudinal axis of the 11.9 × 5.4 m laboratory space, providing adequate clearance from surrounding walls and allowing unobstructed, straight-line walking. Participants turned at the ends of the walkway, outside the motion capture volume, before continuing their next trial. Turns were excluded from the analysis for two reasons: (1) biomechanically, turning introduces complex and non-periodic movements that are not directly comparable to straight-line gait and would confound group-level statistical analyses; and (2) turns occurred outside the calibrated motion capture volume, preventing accurate 3D reconstruction of joint angles during these segments.

Our analysis focused exclusively on steady-state linear walking, which aligns with the study's objective of characterizing lower limb kinematics under controlled conditions. A 3D kinematic model (extended Cleveland Clinic marker set) and an inverse dynamic approach were applied to compute joint angles and moments. Gait events, including initial contact and toe-off, were identified using IntellEvent [14], a deep-learning algorithm, and validated by experts. Each condition captured approximately 23 steps per participant. To obtain the dimensionless gait speed, the equation referring to the Froude number (v*) will be used: $v^* = v/\sqrt{g l_o}$, where v is the speed (m/s), g is the acceleration of gravity (9.81 m/s^2), lo is the length of the lower limb (measurement from the greater trochanter to the ground, in meters). The Froude number was selected because it provides a dimensionless expression of gait speed that accounts for differences in body size by normalizing walking velocity relative to leg length and gravitational acceleration. This enables more meaningful comparisons between individuals with different anthropometric characteristics and reflects the biomechanical principle of dynamic similarity in bipedal locomotion [15].

The assumption of normality was checked by using a Kolmogorov-Smirnov test. We analyzed the temporal profile of the kinematic curves using statistical parametric mapping (SPM) [16] with the open-source package "spm1d" (version 0.4.10) in Matlab. We performed a repeated measures ANOVA comparing RLab and VRLab with and without covarying for dimensionless gait speed. We set the significance level at 0.05.

RESULTS

Of the 21 participants, four said they had never used a VRHMD before, while the remaining had only used it once or twice.

There was a significant difference in dimensionless gait speed (t = 6.68, *p* = 0.001), with higher values for RLab (0.40 ± 0.03) compared to VRLab (0.37 ± 0.03).

Without covarying for dimensionless gait speed (Figure 1), there was a significant difference in (a) the whole gait cycle for pelvic tilt, (b) 1-21%, 37-64% and 84-100% of the gait cycle in pelvic rotation, (c) 1-24% and 97-100% of the gait cycle in hip flexion/extension, (d) 40-44% and 95-97% of the gait cycle in hip add/abduction, (e) 38-43% of the gait cycle in hip int/external rotation, (f) 90-99% of the gait cycle in knee flexion/extension, (g) 1-3%, 46-54%, 60-68% and 97-100% of the gait cycle in knee int/external rotation, (h) 55-63% and 83-88% of the gait cycle in ankle dorsi/plantarflexion, and (i) 54-55% and 85-88% of the gait cycle in ankle inv/eversion.

Covarying by dimensionless gait speed (Figure 2), joint angles had no significant difference. Specifically, SPM{t} analyses yielded non-significant results for all three joints: hip (maximum t = 5.03), knee (maximum t = 6.08), and ankle (maximum t = 3.73). After accounting for gait speed variability, these results confirm that the previously observed kinematic differences were no longer statistically meaningful.

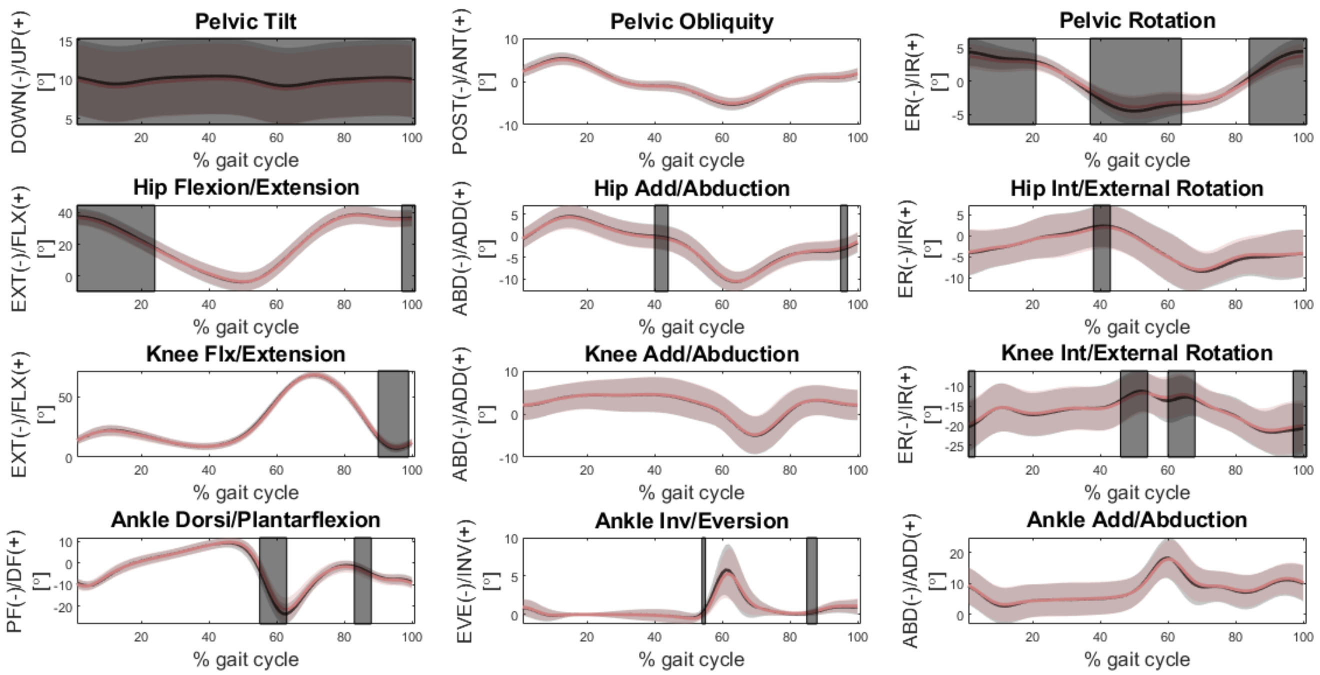

Figure 1. Mean and dimensionless deviation of the hip, knee, and ankle joint angles comparing gait in the Real (red) and Virtual Reality (black) laboratory without covarying for dimensionless gait speed. According to the statistical parametric mapping analysis, the hatched area indicates a significant effect (p < 0.05).

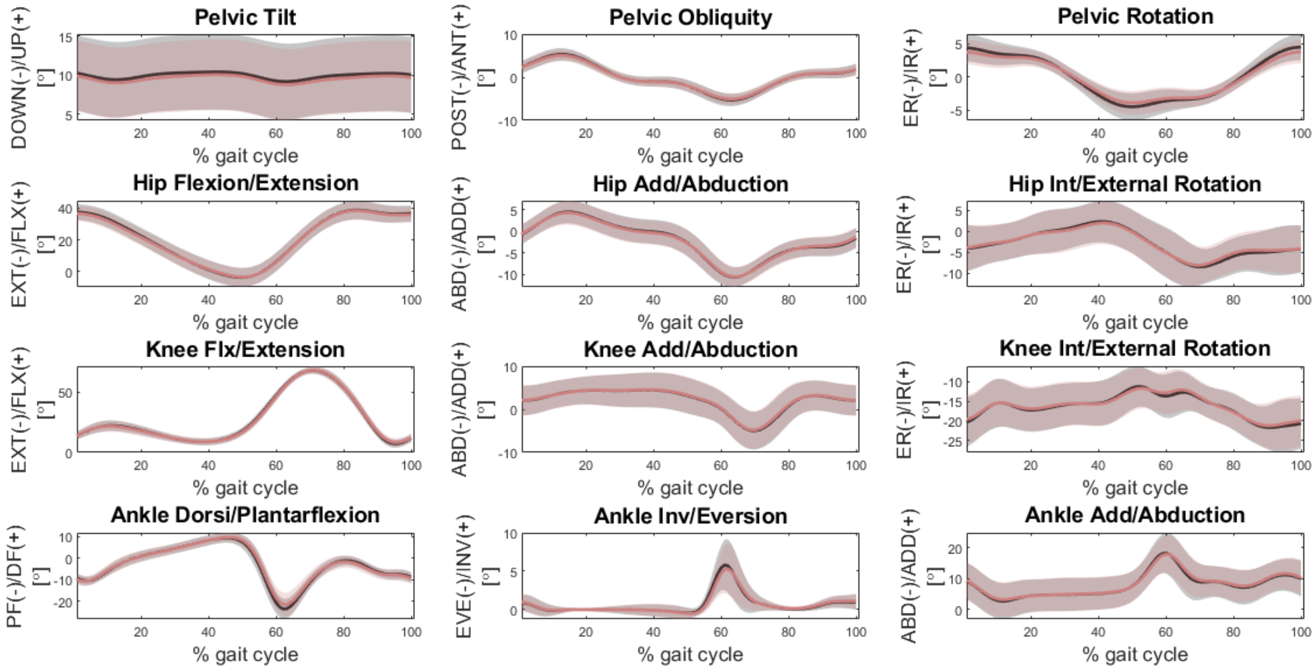
Pelvic Tilt
Pelvic Obliquity
Pelvic Rotation
Hip Flexion/Extension
Hip Add/Abduction
Hip Int/External Rotation
Knee Flx/Extension
Knee Add/Abduction
Knee Int/External Rotation
Ankle Dorsi/Plantarflexion
Ankle Inv/Eversion
Ankle Add/Abduction

Figure 2. Mean and dimensionless deviation of the hip, knee, and ankle joint angles comparing gait in the Real (red) and Virtual Reality (black) laboratory with covarying for dimensionless gait speed.

DISCUSSION

This study advances our understanding of how immersive virtual reality (VR) environments influence human gait by demonstrating that differences in lower limb joint angles during VR walking are primarily attributable to changes in gait speed, rather than to intrinsic biomechanical effects of the virtual context itself. This finding carries significant implications for using VR in gait analysis and rehabilitation, where interpreting motor behavior in these environments requires careful control of behavioral adaptations such as self-selected speed reductions. By disentangling speed-related effects from those due to environmental immersion, our work supports the methodological validity of VR-based assessments. It reinforces their utility in clinical and experimental settings, provided that key confounding variables are adequately addressed. Our data revealed a consistent reduction in gait speed during VR walking, accompanied by statistically significant differences in joint angles when speed was not accounted for. However, when gait speed was included as a continuous covariate in the analysis, these differences disappeared, underscoring the confounding influence of walking velocity on gait kinematics.

The reduced walking speed observed during VR is consistent with previous findings [4–6,10,17]. Slower gait in VR has been interpreted as a cautious strategy to maintain stability in the face of visual-vestibular mismatch, altered proprioceptive feedback, increased cognitive demand or sensory reweighting, or unfamiliar environments [11,12,18]. In particular, using head-mounted displays has increased gait variability and decreased position control, which may contribute to conservative adaptations during locomotion [6,12]. Moreover, environments with visually complex or repetitive patterns—often present in immersive VR—may increase sensory demands, leading to changes in postural and gait control strategies [11].

A key finding of this study is that no significant differences in lower limb joint angles were observed between VR and real-world walking when gait speed was controlled. This significant result suggests that the VR environment does not inherently alter joint kinematics. Although our initial, unadjusted analysis aligned with previous studies, such as Horsak et al. [4], which reported reduced sagittal plane joint excursions in VR, the disappearance of these differences after accounting for speed indicates that the VR condition per se did not drive them. Instead, they appear to be secondary effects of reduced walking speed—a known biomechanical adaptation in immersive environments. This reinforces the idea that gait speed is a powerful confounding factor in gait analysis [7,19]. As shown in the systematic review by Fukuchi et al. [7], walking speed exerts a consistent and significant influence on spatiotemporal variables, joint angles, kinetics, and ground reaction forces. Similarly, Lu et al. [8] demonstrated that walking at preferred speeds promotes more stable and efficient balance control strategies. This further supports the conclusion that gait alterations observed in VR are primarily speed-related rather than environment-induced. Although time normalization to 0–100% of the gait cycle enables phase-aligned comparisons across conditions, this approach may limit the sensitivity of the analysis to absolute timing or speed-dependent biomechanical changes. To overcome this potential limitation, we performed a complementary SPM analysis that included dimensionless gait speed as a continuous covariate. This allowed us to isolate environment-independent effects from those inherently tied to walking speed. The disappearance of significant joint angle differences in this adjusted analysis highlights the importance of controlling for velocity when interpreting VR-induced gait changes, rather than relying solely on temporal normalization. This finding is consistent with prior methodological recommendations[7].

When gait speed was not statistically controlled, joint-angle differences between VR and real-world conditions reached statistical significance across multiple gait cycle phases. While these differences were generally minor, typically below 5 degrees, they may still carry clinical relevance depending on the context. For instance, a 3–5° alteration in knee or ankle kinematics may be functionally negligible in healthy individuals. Still, it could represent meaningful deviations in populations with impaired motor control, such as post-stroke or Parkinson's disease patients. Even subtle kinematic changes in these populations may contribute to inefficient gait patterns, increased energy expenditure, or heightened risk of instability. Thus, although the unadjusted differences in our sample of healthy adults may not translate into immediate functional deficits, they underscore the importance of interpreting gait data in light of both statistical and clinical significance, particularly in rehabilitation applications. Controlling for gait speed is therefore essential in VR gait studies. Without accounting for this factor, researchers may erroneously attribute differences in biomechanical outcomes to the virtual environment when these differences may result from a self-selected reduction in walking velocity. The current results underscore the importance of standardizing walking speed across conditions or statistically controlling for speed during analysis, as suggested in previous work[7,9]. From a clinical and translational perspective, these findings have important implications. VR has been increasingly adopted in rehabilitation protocols for individuals with neurological and musculoskeletal conditions. Understanding how VR influences gait—and under which conditions these effects manifest—is critical for ensuring accurate assessment and effective intervention. Our results suggest that while VR may alter global locomotor parameters such as speed or variability, its direct influence on lower limb joint kinematics is minimal when these confounding factors are accounted for.

This study presents several limitations that should be considered when interpreting the findings. The sample consisted exclusively of healthy adults, which may restrict the generalizability of the results to clinical populations, such as individuals with neurological or musculoskeletal impairments. Additionally, while the virtual environment was constructed to replicate the spatial layout of the real laboratory, it lacked the visual richness, textures, and dynamic elements characteristic of more immersive or ecologically valid VR scenarios. Therefore, gait behavior might differ in more visually complex or novel virtual environments. The relatively short 7-meter walkway, although sufficient to capture steady-state gait in healthy participants, may have limited gait stabilization and induced anticipatory adjustments due to the need for frequent turning. Future studies could benefit from longer walking distances or continuous-loop treadmills to overcome this constraint. Furthermore, the study did not include a formal assessment of simulator sickness or visual fatigue during VR exposure. Although no participant spontaneously reported symptoms such as dizziness or disorientation, and a 5-minute acclimatization period was provided, subtle effects may have gone undetected. Incorporating standardized measures, such as the Simulator Sickness Questionnaire, could help quantify subjective tolerance to immersive VR environments in future research. Future research should explore the underlying mechanisms driving speed reduction and behavioral adaptation in VR. Specifically, the contributions of cognitive load, attentional demand, and sensorimotor integration remain insufficiently understood. Studies employing dual-task paradigms, different levels of visual complexity, and neurophysiological assessments may further elucidate how individuals adjust their gait in immersive environments. Additionally, investigations involving clinical populations or older adults could clarify whether these adaptations differ across age groups or functional capacities.

CONCLUSION

In summary, this study reinforces that walking speed is a primary determinant of gait kinematics in real and virtual settings. VR environments may influence walking behavior by inducing slower, more cautious gait, but do not appear to alter joint angles directly when speed is held constant. These findings contribute to a more nuanced understanding of how immersive technologies interact with motor control and support, using VR as a reliable gait analysis and rehabilitation platform, provided that methodological controls are in place.

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