

Article

Influence of Virtual Reality on Lower Extremity Joint Kinematics During Overground Walking

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Abstract

The inability to regain balance following a trip-induced event is one of the leading causes of falls and fall-related injuries in older adults. Virtual reality (VR) has the potential to expose individuals to realistic environments with minimal injury risk compared to real-world exposures. The purpose of this study was to compare lower extremity joint kinematics during overground walking when exposed to real and virtually generated trip obstacles. A total of 14 healthy participants [7 male, 7 female; age: 23.46 ± 3.31 years; height: 173.85 ± 8.46 cm; mass: 82.19 ± 11.41 kg; shoe size (men's): 9.03 ± 2.71 s] were recruited for this study. Knee and ankle joint kinematics were recorded during obstacle negotiation when exposed to REAL and VR environments. Environmental exposure was assigned in a counterbalanced order to prevent an order effect. Knee and ankle joint kinematics were independently analyzed using a 2×3 repeated measures ANOVA to compare environmental conditions and gait type of the lead leg and trail leg at an alpha level of 0.05. No significant differences were observed between environmental conditions. However, significant differences were observed between gait types of the lead leg and trail leg. Current findings reveal similar gait kinematics during obstacle negotiation when exposed to real and virtually generated trip obstacles, suggesting the potential transfer of skill in fall prevention strategies to real-world conditions.

Keywords: virtual reality; obstacle negotiation; overground walking; gait; trips

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1. Introduction

Falls are the leading cause of injuries and fatalities in older adults over the age of 65 years, affecting over 14 million older adults each year [1]. Although multifactorial in nature, the result of such falls and fall-related injuries have the potential to significantly reduce the ability to perform daily activities, thus leading to weak autonomy, a low mobility lifestyle, and decreased quality of life. Age-related declines in balance performance have been well established in the literature, with impaired postural stability and decreased proprioceptive feedback being the primary causes of declines in balance performance [2]. Balance disturbances due to extrinsic perturbations may also be a potential risk factor for falls, which may include, but are not limited to, uneven walking surfaces and unseen or seen obstacles. Nonetheless, given the susceptibility for injury in older adults, falls often

result in bruises or lacerations, fractures, and a significant fear of falling, potentially leading to an inactive lifestyle and physiological deconditioning [3].

According to the inverted pendulum model, human postural stability and locomotion is mechanically unstable [4]. Maintaining postural stability requires a complex interaction between the central nervous system (CNS) and musculoskeletal system to produce corrective torques across several joints via feedback information from the postural control system. Furthermore, feedback control occurs after a perturbation and is only available when there is no prior knowledge of a specific perturbation [5]. However, given the reactive nature of feedback control for the maintenance of postural stability, feedback responses occur with a delay due to transducing, transmitting, and processing sensory information in order to effectively provide such joint torques [6]. Successful locomotion and restoration of dynamic equilibrium is a time-critical motor skill. Previous literature has demonstrated that a response delay of 100 ms is likely to result in a fall in older adults [7], suggesting the significance of optimal feedforward control to minimize the impact of a perturbation on one's postural stability [8]. The role of reflexes during locomotion when walking on a stable and level surface has been well established [9]. However, rarely does one's walking path involve level surfaces, but rather it often involves changes in elevation or various obstacles. Given the delay of feedback responses when exposed to unexpected perturbations, it is reasonable to assume that optimal feedforward control may be critical in reducing initial postural instability in response to a perturbation. Previous literature has shown the significant role of vision during locomotion as a function of feedforward control related to planning and guidance, as well as obstacle recognition and negotiation [10,11]. Eye tracking data has shown that visual fixation on an obstacle generally occurs at least one to two steps prior to reaching the obstacle and increases based on the obstacle's height and proximity [12]. Thus, successful obstacle negotiation and environmental maneuverability is highly dependent on an individual's ability to recognize obstacles and, as a result, adapt and modify gait kinematics and spatiotemporal parameters. During obstacle negotiation, visual information directly contributes to planning and executing appropriate motor commands to ensure successful obstacle negotiation of the lead leg, while accurate neural representation of the obstacle ensures successful obstacle crossing of the trail leg [13,14]. Therefore, trips are likely to occur when an individual fails to notice an obstacle [15].

Characterizing biomechanical requirements associated with trip recovery and obstacle negotiation is an important aspect in recognizing and determining possible risk factors that may result in fall-related injuries due to trips. A trip occurs when the swing limb unexpectedly makes impact with an object that hinders forward progression of the foot, thus creating a destabilizing scenario of an individual's center of mass (COM) and disturbing one's dynamic equilibrium during the single limb support phase [16,17]. This is accompanied by an anterior shift in the COM and requires a forward step to stabilize dynamic equilibrium [18]. Minimum foot clearance (MFC) is the minimum vertical distance between the lowest point of the foot of the swing leg and the walking surface. This value is approximately 10–20 mm, and it generally occurs around the midswing phase of a gait cycle [19,20]. In addition, it is also the point during the swing phase at which the foot travels at the fastest horizontal velocity [21]. Previous literature has shown that the highest potential for a trip occurs at MFC, where unseen obstacles of 10 mm have a 48 percent chance of causing a trip, but without resulting in a fall, and obstacles that are a height of 12–15 mm have approximately an 80 percent chance of resulting in a trip and fall [15], thus making fall risk from a trip highly dependent on obstacle height. However, MFC is highly sensitive to angular changes as small as 1.35–2.16 degrees at the hip, knee, or ankle [22]. This further emphasizes the importance of visual fixation as a feedforward

control mechanism in appropriately adapting and modifying one's gait characteristics when approaching an obstacle.

Over the past decade, virtual reality (VR) has emerged as a fall prevention training tool due to its potential for skill transfer across environments and populations [23,24]. As VR grows in popularity for research, clinical, and recreational purposes, individuals have the opportunity to immerse themselves in a realistic and interactive environment as a means of improving balance and locomotor function, and VR has been shown to improve overall performance in healthy, injured, and diseased populations [25–28]. These benefits of VR arise due to the potential of exposing individuals to various fall risk hazards with minimal injury risk when compared to real-world exposures, possibly promoting skill transfer and retention via cortical reorganization due to the realistic interaction [29]. Previous studies have investigated gait characteristics and kinematics when exposed to trip obstacles in VR environments during treadmill walking [30–33]. However, lead and trail leg step heights, alongside mean forward velocity, were the only kinematic variables recorded. Additionally, the previous literature has demonstrated that although spatiotemporal gait characteristics may be comparable between treadmill walking and overground walking [34], joint kinematics and joint torques are significantly different between walking conditions, making skill transfer to overground conditions difficult [35,36]. To the authors' knowledge, comparing lower extremity joint kinematics when exposed to real and virtually generated trip obstacles during overground walking has not yet been performed. Moreover, the implementation of comparing lower extremity joint kinematics during overground walking when exposed to real and virtually generated trip obstacles has not yet been examined. Therefore, the purpose of this study was to compare lower extremity joint kinematics about the knee and ankle of the lead leg and trail leg during overground walking when exposed to real and virtually generated trip obstacles in a real and custom designed virtual environment that were exact replicas.

2. Materials and Methods

2.1. Participants

Fourteen healthy young adults [seven male, seven female; age: 23.46 ± 3.31 years; height: 173.85 ± 8.46 cm; mass: 82.19 ± 11.41 kg; shoe size (men's): 9.03 ± 2.71] were recruited for this study. Eligibility criteria included the following: (1) no self-reported history of musculoskeletal, neurological, or vestibular disorders; and (2) a physical fitness level above recreationally trained, defined as engaging in consistent aerobic and anaerobic exercise more than 3–4 days per week for at least three months prior to testing. Participants who reported any risk factors described on the Physical Activity Readiness Questionnaire (PAR-Q) or scored greater than 5 on the Simulator Sickness Questionnaire (SSQ) were excluded [37]. All participants were university students or employees between 18 and 45 years of age.

2.2. Study Design

This study was approved by the Institutional Review Board (IRB) of Mississippi State University under the human subjects protocol number IRB-22-248. A within-subjects repeated measures design was implemented, consisting of two testing sessions: an initial familiarization session and a data collection session.

2.3. Instrumentation

Lower extremity kinematic data was collected using an 8 camera, 3-dimensional (3D) motion analysis system (Motion Analysis Corporation, Cortex version 7.2, Santa Rosa, CA, USA) sampling at 100 Hz. Participants walked at a self-selected pace along a walkway

positioned in the center of the capture area. To ensure participant safety and to reduce the risk of falls, each participant was secure within a fall protection harness (Protecta PRO harness). A Lidar scan was used to create a realistic environment similar to that of the university's Neuromechanics Laboratory, including exact dimensions that allowed for optimal engagement and interaction with the environment. During REAL conditions, participants were exposed to a trip obstacle (43 cm × 16 cm × 22 cm) placed in the center of the walkway. Participants were exposed to a virtually generated obstacle with the same dimensions as the physical obstacle in the REAL condition while wearing the HTC Vive Pro VR headset (HTC America, Inc., Seattle, WA, USA). Figure 1 illustrates the similarities between the REAL and VR environment.



Figure 1. Side by side comparison of REAL (left) and VR (right) environments. Right image contains the trip obstacle present during VR gait trials. Note: no physical trip obstacle was present during VR trials.

2.4. Experimental Procedures

Data collection consisted of a total of two sessions: one familiarization session and one testing session. Informed consent, as well as a completed PAR-Q, International Physical Activity Questionnaire (IPAQ), and a pre-intervention SSQ were obtained during familiarization, based on previous literature [38]. Participants scoring greater than 5 on the SSQ were excluded from participating in this study [37]. Immediately following initial familiarization, participants' general anthropometrics including age, height, mass, and shoe size were recorded. Participants were then provided with a pair of slip-resistant work shoes to avoid possible footwear effects and directed to a 3.5 m walkway to perform several practice gait trials similar to the gait trials to be performed in the REAL environment during data collection. Following the practice gait trials in the REAL environment, participants then donned the VR headset to perform several practice gait trials in the virtual environment. However, during familiarization, no practice trials in which participants were exposed to the trip obstacle used during data collection were administered to prevent a learning effect [39]. Completion of the practice gait trials marked the end of the familiarization session.

Less than a week later, participants arrived at the laboratory for day two of data collection and were given tight-fitting athletic clothing and the same slip-resistant work shoes that were provided during familiarization. Following this, reflective motion capture markers were placed bilaterally on the participant using a lower-body Helen-Hayes model provided in Motion Analysis Cortex to record lower extremity joint kinematics during each gait trial. After preparation, participants were harnessed in a fall arrest system to prevent any fall-related injuries during testing. In the REAL environmental condition, participants were asked to face the opposite direction between each gait trial to prevent any prior knowledge of trip obstacle exposure. Participants were then asked to turn around and walk normally at a self-selected pace, during which lower extremity joint kinematics were recorded for a normal gait trial (NG) as a baseline measurement. Five walking trials were completed under normal conditions where no trip obstacle was present. Following

the final recorded NG trial, a trip obstacle (43 cm × 16 cm × 22 cm) was placed in the center of the walkway without any warning to the participant (unexpected trip: UT), immediately followed by a final gait trial in which the participant was given a warning of the presence of an obstacle (expected trip: ET). A total of 7 trials were conducted for each environmental condition, including NG trials, UT, and ET.

For the VR environmental condition, participants donned the HTC Vive VR headset to perform another set of gait trials in a similar manner. Therefore, gait trials in the VR condition were conducted in the following order: NG, UT, and ET. After donning the VR headset, the distance between the left and right eyes were individualized for each participant to maximize the accuracy of object location in the virtual environment in relation to the physical objects in the physical laboratory. Gait trials were conducted in the exact same manner as the REAL condition, including five NG trials, followed by UT and ET trials. It is important to note that during the UT and ET trials, no physical obstacle was present on the walkway. However, the virtual obstacle present was the exact same dimensions within the virtual environment as the physical obstacle present during the REAL condition.

Following the first environmental condition, participants were given a 10 min rest period. All participants were exposed to both environmental conditions (REAL and VR), with the order of exposure assigned in a counterbalanced order to prevent an order effect.

2.5. Data Analysis

The raw data from Motion Analysis Cortex version 7.0 was cleaned and filtered using a 30 Hz Butterworth filter. All gait trials included from right heel strike of the lead leg prior to reaching the obstacle, to left heel strike of the trail leg after obstacle negotiation, which accounted for an entire gait cycle. Lower extremity joint kinematics were exported to Excel spreadsheets where maximum dorsiflexion, plantarflexion, and knee flexion angles of the lead leg and trail leg were identified. For both the lead leg and trail leg, ankle and knee joint kinematics during UT and ET trials were independently compared to the corresponding unperturbed gait trial (NG) across both environmental conditions (REAL and VR). No data was excluded following analysis.

2.6. Statistical Analyses

A within-subjects 2 (environmental conditions: REAL/VR) × 3 (gait types: NG/UT/ET) repeated-measures analysis of variance (ANOVA) was used to analyze maximum ankle dorsiflexion, plantarflexion, and knee flexion angles individually. Significant main effects were followed up with Bonferroni-adjusted post hoc comparisons. Sphericity was assessed using Mauchly's test, and Greenhouse–Geisser correction was applied when violations were detected. For all analyses, the alpha level was set a priori at $p = 0.05$, and all statistical analyses were performed in JASP software (University of Amsterdam, Nieuwe Achtergracht 129B, Amsterdam, The Netherlands, version 0.18.0, 6 September 2023).

3. Results

3.1. Lead Leg Kinematics

For maximum plantarflexion angle of the lead leg during obstacle negotiation, the repeated measures ANOVA revealed no statistically significant differences between environmental conditions ($F = 1.372$; $p = 0.264$; $\eta_p^2 = 0.103$) or gait types ($F = 0.416$; $p = 0.592$; $\eta_p^2 = 0.033$). Additionally, no statistically significant interactions were observed between gait types and environmental conditions on the lead leg ($F = 1.299$; $p = 0.286$; $\eta_p^2 = 0.098$) (Figure 2).

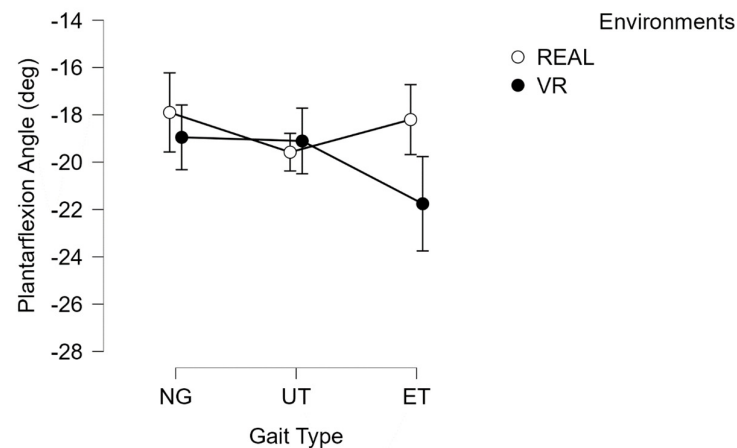


Figure 2. Maximum plantarflexion angle (degrees) during normal gait trials (NG), unexpected trip obstacle exposure (UT), and expected trip obstacle exposure (ET) in both REAL and VR environments.

For maximum dorsiflexion of the lead leg, no statistically significant differences between environmental conditions ($F = 1.083$; $p = 0.319$; $\eta_p^2 = 0.083$) were found. However, there was a significant main effect observed in maximum dorsiflexion angle between gait types ($F = 9.215$; $p < 0.001$; $\eta_p^2 = 0.434$). Furthermore, post hoc comparisons revealed significant differences in maximum dorsiflexion angles during the UT ($p = 0.005$) and ET (0.002) trials when compared to the NG trials. However, no significance was observed when comparing UT and ET trials. Additionally, no significant interactions between gait types and environmental conditions were observed in the lead leg ($F = 2.142$; $p = 0.139$; $\eta_p^2 = 0.151$) (Figure 3).

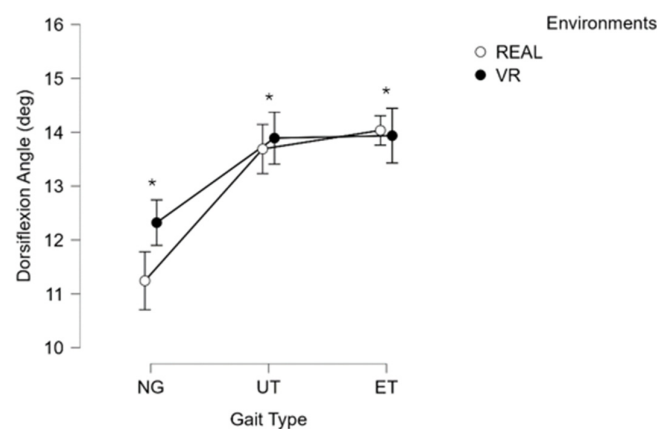


Figure 3. Maximum dorsiflexion angles (degrees) during normal gait (NG), unexpected trip obstacle exposure (UT), and expected trip obstacle exposure (ET) in both REAL and VR environments. Significance is indicated with *.

For the maximum knee flexion angle of the lead leg during obstacle negotiation, no statistically significant differences were observed between environmental conditions ($F = 0.024$; $p = 0.880$; $\eta_p^2 = 0.002$). However, a significant main effect was observed between gait types ($F = 106.185$; $p < 0.001$; $\eta_p^2 = 0.898$). Further, post hoc comparisons revealed significantly greater knee flexion angles of the lead leg during UT ($p < 0.001$) and ET ($p < 0.001$) trials when compared to NG trials. No statistical significance in the maximum knee flexion angle was observed between UT and ET trials. Additionally, no statistically significant interactions were observed between gait types and environmental conditions ($F = 0.916$; $p = 0.413$; $\eta_p^2 = 0.071$) (Figure 4).

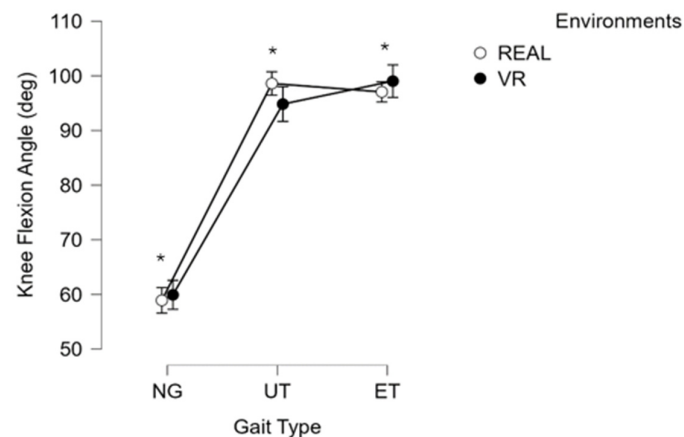


Figure 4. Maximum knee flexion angles (degrees) of the lead leg during normal gait (NG), unexpected trip obstacle exposure (UT), and expected exposure to trip obstacle (ET) in both REAL and VR environmental conditions. Significance is indicated with *.

3.2. Trail Leg Kinematics

For maximum plantarflexion angle of the trail leg, no significant differences were observed between environmental conditions ($F = 0.083$; $p = 0.778$; $\eta_p^2 = 0.006$) or between gait types ($F = 2.941$; $p = 0.071$; $\eta_p^2 = 0.185$). Additionally, no statistically significant interactions were observed between environments and gait types of the trail leg ($F = 1.505$; $p = 0.241$; $\eta_p^2 = 0.104$) (Figure 5).

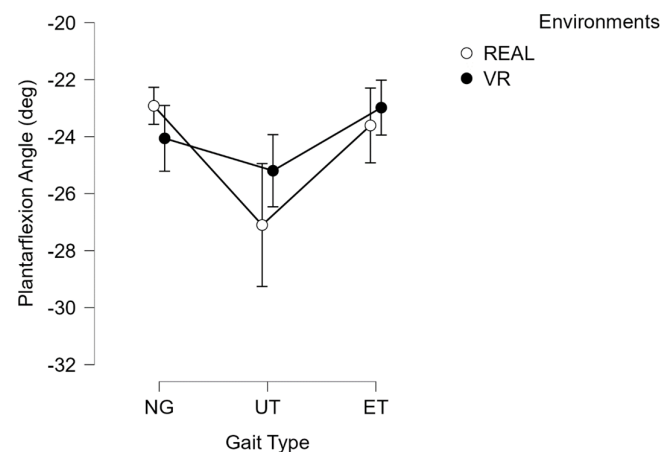


Figure 5. Maximum plantarflexion angle (degrees) of the trail leg during normal gait (NG), unexpected trip obstacle exposure (UT), and expected trip obstacle exposure (ET) in both REAL and VR environmental conditions.

For the maximum dorsiflexion angle of the trail leg, no statistically significant differences were observed between environmental conditions ($F = 0.090$; $p = 0.768$; $\eta_p^2 = 0.007$). However, a significant main effect was observed between gait types ($F = 6.155$; $p = 0.006$; $\eta_p^2 = 0.135$). Post hoc comparisons revealed that significantly greater maximum dorsiflexion angle was observed during UT ($p = 0.027$) and ET ($p = 0.010$) trials compared to NG trials. No statistically significant interactions were observed between environmental conditions and gait types ($F = 2.027$; $p = 0.152$; $\eta_p^2 = 0.135$) (Figure 6).

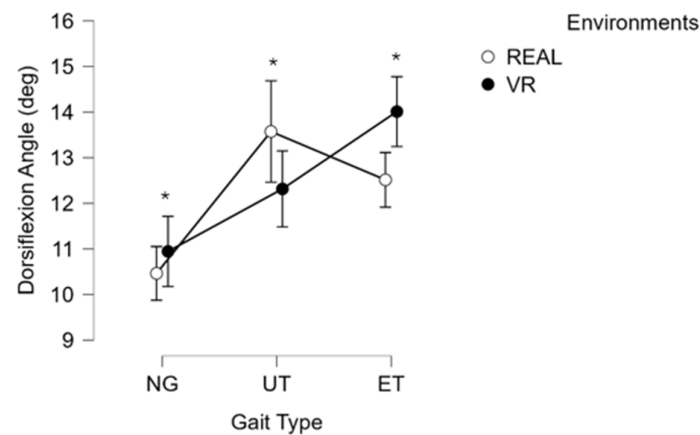


Figure 6. Maximum dorsiflexion angle (degrees) of the trail leg during normal gait (NG), unexpected trip obstacle exposure (UT), and expected trip obstacle exposure (ET) in both REAL and VR environmental conditions. Significance is indicated with *.

For maximum knee flexion of the trail leg, results revealed no statistically significant differences were observed between environmental conditions ($F = 0.396$; $p = 0.540$; $\eta_p^2 = 0.030$). However, significant differences in maximum knee flexion angle of the trail leg were observed between gait types ($F = 96.775$; $p < 0.001$; $\eta_p^2 = 0.882$). Post hoc comparisons revealed significantly greater maximum knee flexion angle during UT ($p < 0.001$) and ET ($p < 0.001$) compared to NG trials. No statistically significant interactions were observed between environmental conditions and gait types ($F = 0.277$; $p = 0.643$; $\eta_p^2 = 0.021$) (Figure 7).

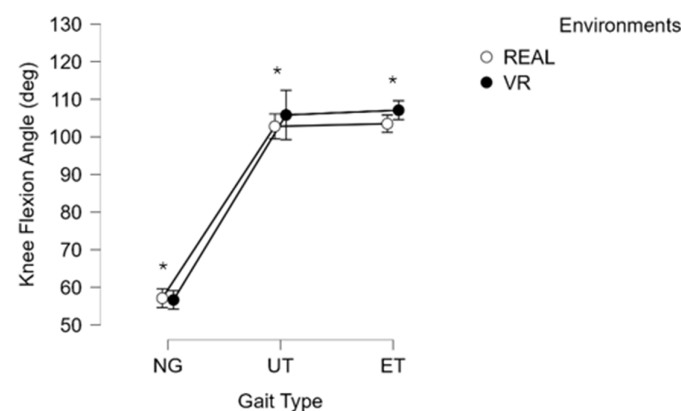


Figure 7. Maximum knee flexion angle (degrees) of the trail leg during normal gait (NG), unexpected trip obstacle exposure (UT), and expected trip obstacle exposure (ET) in both REAL and VR environmental conditions. Significance is indicated with *.

Table 1 summarizes lower extremity joint kinematics about the knee and ankle joints in terms of degrees of flexion of the lead leg and trail leg. Lower extremity joints and leg were independently analyzed across environmental conditions (REAL and VR) and trial type (NG, UT, ET). Considering the anatomical neutral position of the ankle joint as zero degrees on the Y-axis, maximum plantarflexion is reported as a negative value and maximum dorsiflexion is reported as a positive value (Table 1).

Table 1. Summary of lower extremity joint kinematics about the knee and ankle joints of the lead leg and trail leg across gait trial type (NG, UT, ET) and environmental conditions (REAL, VR).

Environment	Joint	Leg	NG (Degrees)	UT (Degrees)	ET (Degrees)
REAL	Plantarflexion	Lead	-17.90 ± 6.39	-19.58 ± 7.92	-18.20 ± 8.63
		Trail	-22.92 ± 8.84	-27.10 ± 12.34	-23.61 ± 9.31
	Dorsiflexion	Lead	11.24 ± 4.91	13.69 ± 3.46	14.04 ± 3.93
		Trail	10.46 ± 4.27	13.54 ± 6.86	12.52 ± 4.93
	Knee Flexion	Lead	58.91 ± 5.24	98.60 ± 15.10	97.05 ± 9.92
		Trail	57.10 ± 5.50	102.78 ± 15.62	103.49 ± 9.98
Virtual (VR)	Plantarflexion	Lead	-18.95 ± 6.12	-19.11 ± 8.87	-21.11 ± 10.49
		Trail	-24.06 ± 7.76	-25.20 ± 8.45	-22.98 ± 6.34
	Dorsiflexion	Lead	12.32 ± 4.33	13.89 ± 2.96	13.94 ± 4.49
		Trail	10.95 ± 5.27	12.32 ± 6.04	14.01 ± 6.22
	Knee Flexion	Lead	59.91 ± 4.50	94.83 ± 19.01	99.02 ± 19.26
		Trail	56.65 ± 6.31	105.83 ± 31.32	107.08 ± 14.54

4. Discussion

With the growing popularity of virtual reality in research, clinical, and leisurely settings, the purpose of the current study was to compare lower extremity joint kinematics when exposed to real and virtually generated trip obstacles during overground walking. To do this, a virtual environment was designed that was an exact replica of the physical laboratory environment. It was hypothesized that lower extremity joint kinematics would be similar between environmental conditions. Previous literature has investigated whole body kinematics in virtual environments during reaching tasks and lower extremities training [40,41]. However, to the authors' knowledge, comparing lower extremity joint kinematics when exposed to real and virtually generated trip obstacles during overground walking using immersive VR has not yet been performed. The current study was unique as an exact replica virtual environment similar to the physical environment was used during data collection, intended to provide the most realistic immersion possible.

In line with our hypothesis, the current study revealed no significant differences in lead leg or trail leg joint kinematics when exposed to REAL and VR environmental conditions. Previous literature has demonstrated the potential benefits of using VR as a means of locomotor training and balance therapy in injured, clinical, and older populations [42–45]. In fact, balance training using consistent, repeated exposure to virtual environments while performing balance drills has been shown to significantly improve static and dynamic balance in individuals with functional ankle instability [46], improved gait parameters such as gait speed, cadence, step length, and single limb support [47], and in some cases has elicited greater improvements in performance compared to traditional rehabilitative methods [48]. Thus, given the fundamental nature of human locomotion for everyday activity, it is reasonable to assume that repeated exposure to virtually generated trip obstacles has the potential to improve one's ability to successfully navigate their environment.

Additionally, the current findings revealed significantly greater knee flexion angles and ankle dorsiflexion angles during obstacle negotiation in both environments compared to normal gait trials with no obstacle present. However, no differences in gait kinematics were observed between environmental conditions during obstacle negotiation trials. Walking is a fundamental motor skill that requires a high degree of sensorimotor transformation to ensure appropriate adaptation to one's environment. Given the essential component of gait

adaptation to successfully navigate through unpredictable circumstances, it is reasonable to assume that repeated exposure to virtually generated trip obstacles has the potential to effectively transfer to real-world situations. Previous literature has shown that the ability to effectively modify gait characteristics occurs through sensory input from the limbs [49]. Additionally, repeated complex obstacle negotiation training has been shown to significantly improve obstacle negotiation performance in individuals with Parkinson's disease, revealing improvements in stride length, cadence, and gait speed [50]. In fact, Yamada et al. (2012) revealed that complex obstacle negotiation resulted in greater obstacle negotiation performance, greater postural control, and resulted in a lower incidence rate of falls and fractures 12 months following a 24 week intervention [51]. Therefore, repeated VR obstacle negotiation training may have the potential to improve one's ability to effectively navigate one's physical environment.

Finally, similar to previous literature, the current study revealed no significant differences in lower extremity joint kinematics when comparing UT and ET trials. However, the current study specifically investigated obstacle negotiation in young adults. While the current study revealed no significant differences in lower extremity joint kinematics during UT and ET trials, the previous literature has shown that older adults alter their obstacle negotiation strategies when exposed to anticipated obstacles compared to unanticipated obstacles [52]. Additionally, although successful obstacle negotiation seems to be highly dependent on obstacle height in younger and middle-aged adults, specifically higher, unseen obstacles seem to produce a lower success rate [15], other literature suggests lower, unseen obstacles produce a lower success rate in older adults [52]. This may be due to age-related changes in gait characteristics, such as altered stride length, gait speed, and MFC. Moreover, these age-related physical changes may be attributed to age-related deterioration of general processing mechanisms during time-constrained situations [53].

It is worth noting that aging and neurological impairments may affect an individual's level of learning, retention, and transfer. Neurodegenerative changes due to various conditions such as Parkinson's disease and cerebellar degeneration have the potential to significantly impact one's short-term retention and motor learning capacity [54,55]. Additionally, overground walking while using immersive VR has been shown to significantly increase variability in trunk kinematics in younger individuals [56]. However, the current study investigated the effects of immersive VR on lower extremity joint kinematics during overground walking and revealed no significant differences between environmental conditions. Other studies have revealed no deficits in learning and retention in individuals with Parkinson's disease when using VR for balance and locomotor rehabilitation, although exercise selection was identified as a critical element when using VR for rehabilitation purposes in Parkinson's disease [57,58]. Moreover, when considering VR for balance and locomotor rehabilitative purposes, specific overground gait training seems to provide the highest transfer to real-world scenarios [54,59], thus suggesting potential of using VR as a means of fall prevention.

The current study compared lower extremity joint kinematics when exposed to real and virtually generated trip obstacles during overground walking. The results revealed similar lower extremity joint kinematics between environmental conditions, but it does not compare long-term effects of VR exposure in terms of potential training effects. Another limitation includes that the participants tested were young adults. Although previous literature has shown similar benefits in VR gait training in younger and older adults [60], future research should investigate the long-term balance and locomotor effects of VR gait training in overground walking scenarios in older adults. Additionally, although unexpected and expected conditions were utilized during gait trials in which participants

were exposed to the trip obstacle, better methods implementing unexpected exposures should be investigated in future research.

5. Conclusions

The current study revealed similar lower extremity joint kinematics during obstacle negotiation when exposed to real and virtually generated trip obstacles, suggesting the potential benefit of using VR for fall prevention. Therefore, repeated exposure to virtually generated trip obstacles may have the potential to improve one's ability to effectively navigate the environment without increasing injury risk due to such exposures in real-world settings. The current study uniquely exposed individuals to a virtual environment that was an exact replica of the physical laboratory during overground walking. However, further research is required and should focus on the long-term benefits of obstacle negotiation training when exposed to virtually generated trip obstacles during overground walking in various settings. Additionally, because of the differences in younger and older adults' responses to the presence of obstacles, future research should investigate the long-term gait training effects of VR immersion during overground walking in older adults.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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