

Article

Effects of Acute Exposure to Virtually Generated Slip Hazards during Overground Walking

Hunter Derby^{1,*}, Nathan O. Conner¹, Jacob M. Hull¹, Faith Hagan¹, Sally Barfield¹, Timothy Stewart², J. Adam Jones², Adam C. Knight¹ and Harish Chander¹

¹ Neuromechanics Laboratory, Mississippi State University, Mississippi State, MS 39762, USA; noc13@msstate.edu (N.O.C.); jmh1521@msstate.edu (J.M.H.); flh98@msstate.edu (F.H.); skh342@msstate.edu (S.B.); aknight@colled.msstate.edu (A.C.K.); hchander@colled.msstate.edu (H.C.)
² High Fidelity Virtual Environments Lab (Hi5 Lab), Mississippi State University, Mississippi State, MS 39762, USA; ts2475@msstate.edu (T.S.); jones@cse.msstate.edu (J.A.J.)
* Correspondence: hcd89@msstate.edu

Abstract: Postural instability and the inability to regain balance during slip-induced events are the leading causes of falls on the same level in occupational environments. Virtual reality (VR) provides the potential to be immersed in a realistic environment, exposing themselves to fall-risk hazards without the risk of injury real-world exposure may cause. Therefore, the purpose of this study was to compare the lower extremity joint kinematics of the slipping leg during real and virtually generated slip hazards. A secondary purpose was to investigate dynamic postural stability following acute exposure to real (REAL) and virtual (VR) environmental conditions. A total of 14 healthy participants' (7 men, 7 women; age: 23.46 ± 3.31 years; height: 173.85 ± 8.48 cm; mass: 82.19 ± 11.41 kg; shoe size (men's): 9.03 ± 2.71) knee and ankle joint kinematics were compared during exposure to both REAL and VR environments. Participants then completed a series of Timed Up-and-Go (TUG) variations (standard, cognitive, manual) at the beginning and the end of exposure to each environment. TUG-C involved backwards counting and TUG-M involved walking with an anterior load. Environmental exposure was selected in a counterbalanced order to prevent an order effect. Knee and ankle joint kinematics were analyzed separately using a 2×3 repeated measure ANOVA to compare environments as well as gait types at an alpha level of 0.05. TUG variations were also analyzed separately using a 3×3 repeated-measures ANOVA to compare TUG variations and environment. No significant differences were observed for knee or ankle joint kinematics between environments or gait types. There were also no significant interactions between environments and gait types. However, significant differences were observed for TUG-C following VR environmental conditions ($p = 0.027$). Post hoc comparisons revealed significantly lower times for TUG-C following VR exposure ($p = 0.029$). No significance was observed for TUG-S or TUG-M. Current findings suggest the potential effectiveness of VR as a means of fall prevention training for occupational populations based on improved TUG-C and similar lower extremity joint kinematics in REAL and VR conditions.

Keywords: virtual reality; gait training; postural stability; overground walking; slips



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1. Introduction

Falls are one of the leading causes of injuries and fatalities in occupational environments, along with one of the leading causes of time away from work, specifically among construction and manufacturing, making fall prevention efforts a necessity among occupational populations. Exposure to various slip hazards such as slippery or uneven surfaces and debris has been recognized as a significant influence on falls and fall-related injuries [1]. In fact, according to the Bureau of Labor Statistics (BLS), injuries due to slips, trips, and falls accounted for 46.1% of total workplace injuries in construction settings [2]. Such

injuries can result in permanent disability, loss of earning potential, poor quality of life, and significant financial burdens for the employee and employer. Moreover, more than one-third of the total number of fatalities in the construction industry were a result of falls due to slips and trips [2]. Although there was a reduction in the number of falls in construction from 2019 to 2020 in the United States, there was a 5.9% increase from 2020 to 2021 [2]. Moreover, slips have been recognized as the most common cause of falls at the same level and have continued to show an upward trend in being the primary cause of falls and fall-related injuries by approximately 25% in the last 10 years [3]. However, an individual's fall risk is highly dependent on their physical ability to recover from the initial perturbation that triggers instability [4]. Some of the most common causes of falls and fall-related injuries are inefficient postural control strategies and the failure of normal locomotion and equilibrium in response to significant perturbations [5], resulting in a loss of postural stability, and ultimately could be a result of improper functioning of an individual's sensory feedback stimuli provided by the postural control system (visual, vestibular, and proprioception) [6,7]. In order to prevent falls, one must be capable of producing coordinated movements across several joints to allow for proper recovery from a perturbation. Therefore, optimal coordination of one's neuromuscular and skeletal systems is critical to regain postural stability.

According to the National Occupational Research Agenda (NORA) for construction, falls from a height and the same levels are top priorities for the Center for Disease Control and Prevention (CDC) [8], highlighting the significance of falls and fall-related injuries in occupational environments. The increased probability of occupational falls and the mechanisms behind such falls are complex and can involve various extrinsic environmental factors, such as walking surfaces, or individual intrinsic human factors, such as muscular fatigue, that may impact postural stability. Due to the inconsistency and variability of construction worksites, there remains a high risk of exposure to slip hazards. Therefore, gait patterns must be regularly modulated and corrected to avoid these slip hazards. Primarily, research related to fall prevention due to slips has focused on the environmental factors, including the coefficient of friction experienced by the shoe–floor interface when exposed to a slippery walking surface, which is recognized as a major predictor of slip events [9]. Heel slip distance and heel slip velocity following heel strike during human locomotion are commonly utilized to differentiate slip types and fall risk [10]. Additionally, lower extremity joint kinematics, although less common, may also be used to determine possible contributions to forward heel slipping [11,12]. While falls related to walking are initially provoked by environmental factors such as slippery or uneven walking surfaces, slopes, etc., the fall itself is determined based on an individual's characteristics that may allow them to recover from the perturbation. Therefore, due to the individualistic nature of one's slip recovery patterns, it is critical to link lower extremity joint kinematics to an individual's functional anatomy to determine fall risk from slip hazard exposure [13,14].

In general, biomechanical analyses of postural responses during slip-induced falls are performed during exposure to slip hazards during locomotion in both real-world and laboratory-based environments [11,15–17]. With the growing popularity of virtual reality (VR), VR has been utilized as a means of assessment for postural control and stability and has been shown to be a promising tool for improving balance performance, especially among the elderly [18–21]. Additionally, various movement pattern training programs involving VR have been shown to be effective in improving locomotor patterns, sensory, and muscle coordination in stroke patients [22], individuals with Parkinson's disease [23], multiple sclerosis [24], and injured individuals [25,26], thus improving their ability to recover from slip-induced falls. Given that retention is an essential function of the central nervous system (CNS), and improvement in specific skills requires repeated exposure to cause adaptation, VR has the potential to immerse individuals in a realistic and interactive environment to allow for effective training and adaptation without the risk of injury real-world exposure may cause. Although both immersive and non-immersive VR have been shown to be effective for various purposes, immersive VR allows for a more engaging

and interactive experience that can mimic real-world exposure [27]. Additionally, Timed Up-and-Go (TUG) is a quick and simple test commonly used in clinical settings to assess an individual's lower extremity function, mobility, and ability to navigate one's environment. Although often used in elderly populations, TUG can also be used in research settings in healthy adults with a dual-task component to provide a more accurate evaluation of dynamic postural stability and neurocognitive function. Dual-task TUG involving manual or cognitive components has been reported as a more appropriate measure of healthy individuals' physical abilities due to the fact that most everyday activities involve dual-task components [28,29].

With a projected compound annual growth rate (CAGR) of 7.3% by the year 2029, the construction industry is one of the fastest-growing industries in the United States [30]. Moreover, because of the high prevalence of falls in the construction industry, there is a need to pursue feasible tools for assessments and training to promote occupational safety and health. Although initially more expensive, VR can be used for a larger number of participants for a longer period of time, reducing overall cost by hundreds of dollars per participant [31]. VR seems to be an appropriate and feasible tool for fall prevention training by exposing individuals to various situations and environments to promote greater locomotor adaptations. Previous literature has demonstrated significant improvements in postural stability and balance performance after exposure to VR [32]. Additionally, previous literature has shown similar gait characteristics and lower extremity joint kinematics when comparing real-world and VR environment exposure during treadmill walking [33]. However, to the authors' knowledge, no previous studies have compared lower extremity joint kinematics during overground walking between real-world and VR exposure where the VR environment is an exact replica of the real environment in which data are collected. Therefore, the purpose of this study was to investigate lower extremity kinematics of the knee and ankle of the slipping leg when exposed to slip hazards during real and virtually generated slip hazards during overground walking. An additional purpose of this study was to determine the effectiveness and feasibility of a fall prevention training program that involves repeated exposure to virtually generated slip hazards compared to a real environment. This study further attempted to determine fall risk during dynamic postural control tasks using several Timed Up-and-Go variations following exposure to real-world (REAL) and VR environments (VR).

2. Materials and Methods

2.1. Participants

A total of 14 healthy participants (7 men, 7 women; age: 23.46 ± 3.31 years; height: 173.85 ± 8.48 cm; mass: 82.19 ± 11.41 kg; shoe size (men's): 9.03 ± 2.71) with no self-reported history of any musculoskeletal, neurological, cardiovascular, or vestibular disorders were recruited for this study. Participants' physical fitness status was also above recreationally trained (>3–4 days with consistent aerobic and anaerobic training) for at least 3 months prior to testing. Any participants with risk factors and/or simulator sickness questionnaire (SSQ) scores greater than 5 were excluded from the study [34]. All participants were university students or employees between 18 and 45 years of age.

2.2. Study Design

The study was approved by the Mississippi State University's Institutional Review Board (IRB) under human subjects research protocol number IRB-22-156. The experiment followed a within-subjects repeated-measures design and consisted of a total of 2 days of testing: one initial familiarization day and one day of data collection. Initial familiarization involved the completion of the informed consent document, followed by the completion of a physical activity readiness questionnaire (PAR-Q) and an international physical activity questionnaire (IPAQ); an initial pre-intervention SSQ was provided as suggested by Bimberg et al., 2020 [35]. Participants scoring greater than a score of 5 on the SSQ were excluded from participating in this study [34].

2.3. Instrumentation

Lower body joint kinematics were recorded using an 8-camera, 3-dimensional (3D) motion capture system (Motion Analysis Corporation, Cortex version 7.2, Santa Rosa, CA, USA) at a sampling rate of 100 Hz. Participants performed a series of gait trials on a walkway placed in the center of the motion capture volume. In order to prevent fall-related injuries during data collection, participants wore a fall arrest harness (Protecta PRO harness). For the VR gait trials, participants were exposed to the VR environment using the HTC Vive Pro (HTC America, Inc. Seattle, WA, USA). A Lidar scan was used to create an exact replica of the university's Neuromechanics Laboratory, which included exact dimensions of the lab that allowed the participants to engage with the environment. During the REAL condition, participants were exposed to a slip hazard that was placed in the center of the walkway that was positioned in the center of the laboratory space. The slip hazard included a liquid contaminant of 75% glycerol and 25% water. Similarly, during the VR condition, participants were exposed to a virtually generated slip hazard using the HTC Vive Pro VR headset in the same format as the REAL condition; the slip hazard was placed in the center of the walkway. Similarities between the REAL and VR environments are illustrated in Figure 1.



Figure 1. Side-by-side comparison of REAL (left) and VR (right) environments. Lower extremity joint kinematics were recorded when the participant walked across the gray walkway in the center of the lab.

2.4. Experimental Procedures

Data collection consisted of a total of two days: one familiarization day and one testing day. Following initial familiarization during day one, each participant's age, height, mass, and shoe size were recorded. Participants were then provided a pair of slip-resistant work shoes to be worn during baseline balance testing and during the practice gait trials. The same shoes would be worn during day two of data collection. Several Timed Up-and-Go (TUG) tests were then completed, which previous literature explains are a predictor of one's ability to maneuver an environment with relative safety [36]. These included a standard TUG (TUG-S), cognitive TUG (TUG-C), and a manual TUG (TUG-M). The standard TUG involved the participant sitting in a chair, then, on command, walking 3 m, turning around, walking back to the chair, and sitting down. Similar to the TUG-S, TUG-C involved the same task but included counting backward from 100 by a number that was randomly assigned prior to each trial. Finally, participants completed TUG-M, which is similar to the standard TUG, with a standard anterior load of 15 lb. assigned to all participants to be carried throughout the test. Additionally, because the participants would be exposed to VR during data collection, all participants were exposed to the virtual environment and given the opportunity to perform several gait trials across a walkway located in the center of the lab, both in the REAL and VR environments. However, during familiarization, no practice trials in which the participants were exposed to the slip hazards were administered in order to avoid a learning effect [37]. Completion of the practice gait trials marked the end of day one of testing.

Less than a week later, upon arrival for day two of data collection, participants were given tight-fitting athletic clothes and the slip-resistant work shoes they wore during baseline testing. Reflective motion capture markers were then attached bilaterally using a lower-body Helen–Hayes model provided in Motion Analysis Cortex. After preparation, the participants were directed to the walkway and placed in the fall arrest system to prevent fall-related injuries during testing. During the REAL condition, participants were asked to walk at a self-selected pace across the dry walkway with no slip hazard present while their lower body joint kinematics were recorded during a normal gait (NG) trial as a baseline measurement. Following the NG trial, the slip hazard was placed in the middle of the walkway without any warning (unexpected slip: US), followed by an additional slip perturbation trial with a warning (expected slip: ES). NG was recorded for each participant before exposure to the slip hazard, making a total of 3 trials recorded: NG, US, and ES.

Following these trials (NG, US, ES) in the REAL condition, all 3 TUG variations were performed again followed by a 10-minute rest period given to the participants to reduce the potential for the development of fatigue. Participants then donned the HTC Vive VR headset to perform the same trials in a similar manner. Therefore, gait trials were performed in the VR condition in the following order: NG, US, and ES. Immediately following exposure to the VR environment, participants then completed a post-intervention SSQ to assess the effects of the VR environment on the participant. Participants then completed another series of TUG-S, TUG-C, and TUG-M. Completion of all the TUG variations marked the end of data collection. All participants were exposed to both environmental conditions during testing. The order of exposure to environmental conditions (REAL and VR) was assigned in a counterbalanced order.

2.5. Data Analysis

The raw data from Cortex version 7.0 were cleaned by removing unlabeled markers, the gaps were filled and filtered using a 30 Hz Butterworth filter. All gait trials were trimmed from the left heel strike to the right heel strike following the completion of a complete gait cycle. Maximum dorsiflexion and maximum plantarflexion angles along with maximum knee flexion angles were determined upon exporting joint kinematics data into Excel sheets. Ankle joint and knee joint kinematics during the US and ES during both environmental conditions (REAL/VR) were compared to the corresponding data collected during the unperturbed gait trial (NG).

2.6. Statistical Analyses

Both maximum ankle dorsiflexion and maximum plantarflexion angles and maximum knee flexion angles were individually analyzed using a 2 (environmental condition: REAL, VR) \times 3 (gait: NG, US, ES) repeated-measures analysis of variance (ANOVA). Any significant main effects were further analyzed using Bonferroni post hoc comparisons. Additionally, TUG-S, TUG-C, and TUG-M were analyzed separately using repeated-measures ANOVA to determine any main effects observed at the different timepoints within data collection: pre-testing, post-REAL, and post-VR (BL, REAL, VR). Any significant main effects were further analyzed using Bonferroni post hoc comparisons. SSQ data were analyzed using a paired samples t-test to determine any significance between pre-test and post-test scores within subjects. The significance level was set with an alpha level of 0.05 a priori. Machuly's test was used for sphericity tests and Greenhouse–Geisser correction was used if there was a violation of sphericity. Additionally, a Shapiro–Wilk test was used to test for normality. All statistical analysis was conducted using JASP statistical software (University of Amsterdam, Nieuwe Achtergracht 129B, Amsterdam, The Netherlands, version 0.18.0, 6 September 2023).

3. Results

For maximum plantarflexion angle on the slipping leg, the repeated-measures ANOVA revealed no statistical significance between gait type ($F = 0.473$; $p = 0.629$; $\eta_p^2 = 0.041$) or

environmental conditions ($F = 0.311$; $p = 0.588$; $\eta_p^2 = 0.011$). Additionally, there was no significant interaction between environmental condition and gait type for the maximum plantarflexion angle on the slipping leg ($F = 1.136$; $p = 0.339$; $\eta_p^2 = 0.025$) (Figure 2).

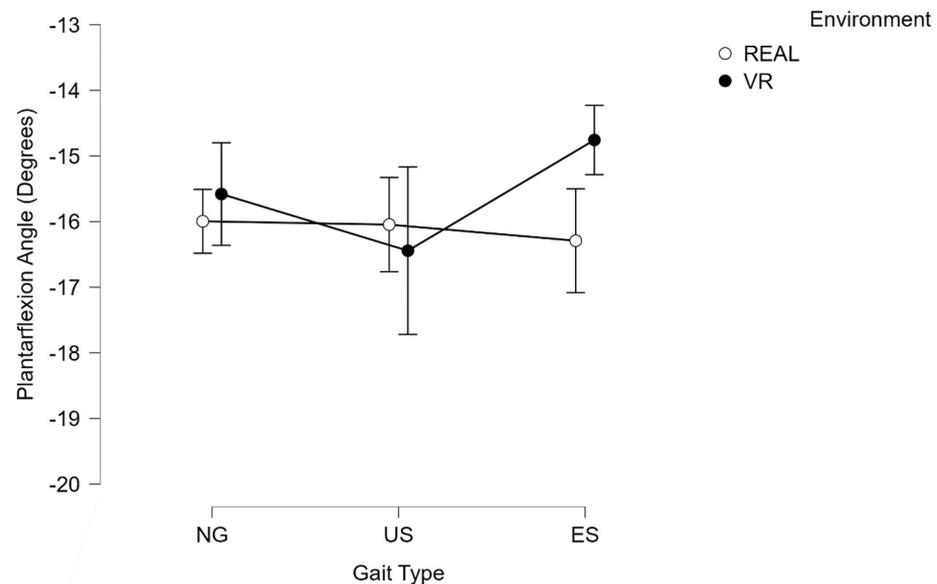


Figure 2. Maximum plantarflexion angle (degrees) during normal gait (NG), unexpected slip (US), and expected slip (ES) in both REAL and virtual VR environments.

For maximum dorsiflexion angle on the slipping leg, there was also no statistically significant difference between gait type ($F = 2.328$; $p = 0.119$; $\eta_p^2 = 0.162$) nor between environmental conditions ($F = 3.299$; $p = 0.094$; $\eta_p^2 = 0.216$). There were also no significant interactions observed between environmental condition and gait type for the maximum dorsiflexion angle on the slipping leg ($F = 1.758$; $p = 0.194$; $\eta_p^2 = 0.128$) (Figure 3).

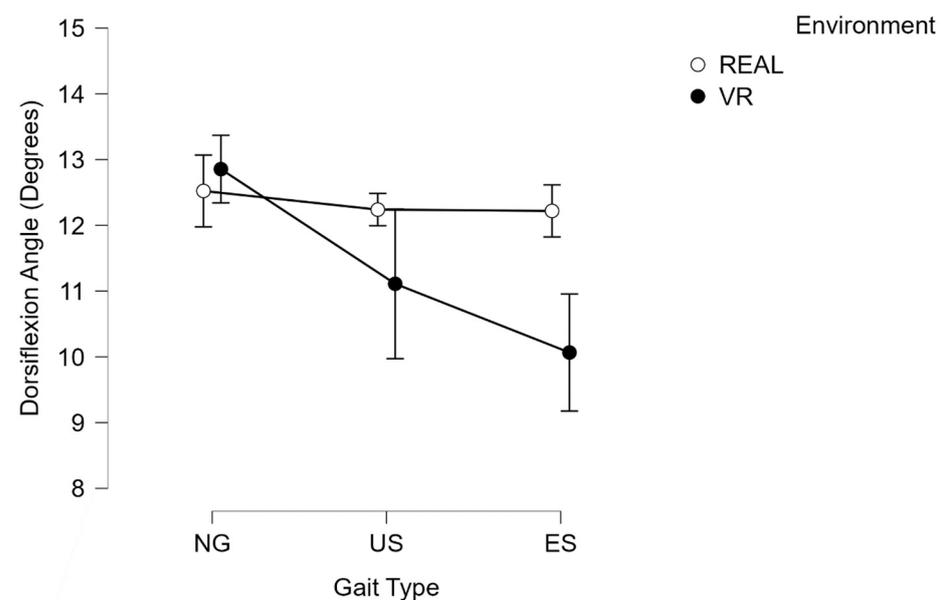


Figure 3. Maximum dorsiflexion angle (degrees) during normal gait (NG), unexpected slip (US), and expected slip (ES) in REAL and virtual (VR) environments.

For the maximum knee flexion angle of the slipping leg, no statistically significant difference was observed between the environmental conditions ($F = 1.077$; $p = 0.322$, $\eta_p^2 = 0.089$) and for gait type ($F = 2.250$; $p = 0.129$, $\eta_p^2 = 0.170$). There was also no

statistically significant interaction between environment and gait type ($F = 0.990$; $p = 0.388$, $\eta_p^2 = 0.083$) (Figure 4).

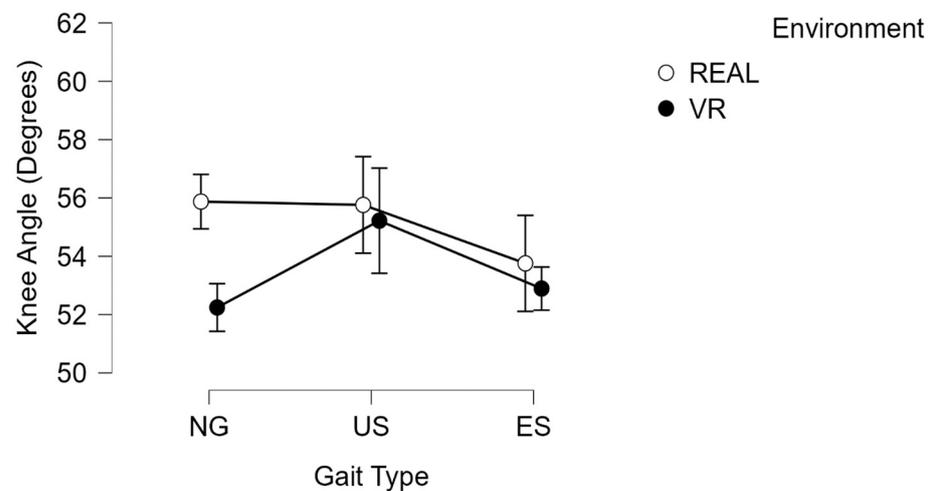


Figure 4. Maximum knee joint flexion angle (degrees) during normal gait (NG), unexpected slip (US), and expected slip (ES) in both real and virtual (VR) environments.

For SSQ, the paired-samples t-test did not show any significance in scores when comparing before and after exposure to the VR environment ($p = 0.668$) (Figure 5).

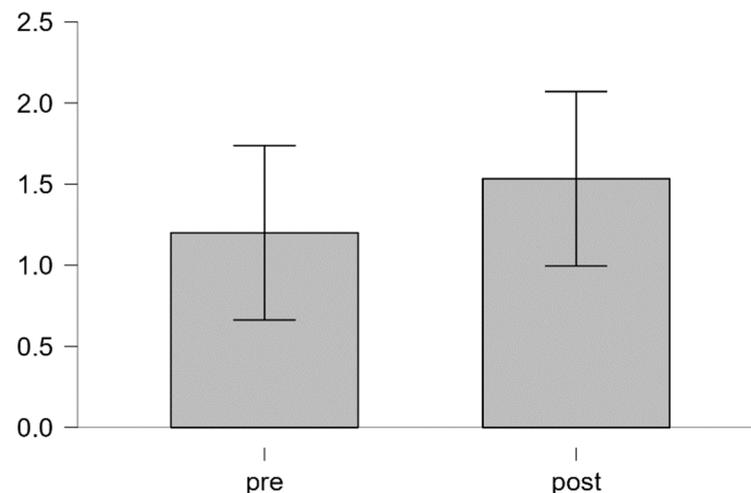


Figure 5. Simulator Sickness Questionnaire (SSQ) scores before (pre) and after (post) exposure to virtual (VR) environments.

For TUG, a significant main effect was observed for TUG-C ($F = 4.413$; $p = 0.027$; $\eta_p^2 = 0.240$). Post hoc comparisons revealed significantly lower times following exposure to VR environments compared to baseline (BL) and REAL environment exposure ($p = 0.023$). However, no significant differences were revealed for TUG-S or TUG-M. Additionally, significant differences were revealed between environmental conditions ($F = 4.304$; $p = 0.027$; $\eta_p^2 = 0.235$). Post hoc comparisons revealed significantly lower times following VR exposure ($p = 0.029$). Significance was also observed among comparisons of TUG variations ($F = 15.808$; $p < 0.001$; $\eta_p^2 = 0.530$). Post hoc comparisons revealed significantly higher times of completion for the TUG-C when compared to TUG-S ($p < 0.001$) and TUG-M ($p < 0.001$). The results did not show any significant interactions between environmental conditions and TUG variations (Figure 6).

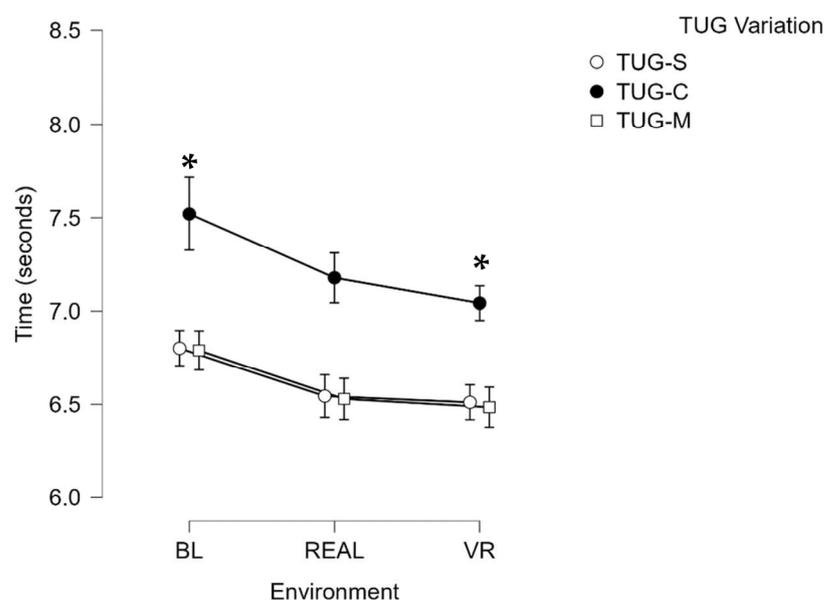


Figure 6. Time to completion for all three Timed Up-and-Go (TUG) variations in each at baseline (BL) and after exposure to REAL and VR environments. Significance differences are indicated with *.

4. Discussion

The purpose of the current study was to investigate differences in lower extremity joint kinematics when exposed to REAL and VR environments. Previous literature has investigated changes in static and dynamic postural stability after being exposed to VR in the elderly, diseased, and injured [26,38,39]. Additionally, several researchers have examined gait characteristics and joint kinematics when exposed to slip events during loaded conditions and unloaded conditions [40,41]. However, to the authors' knowledge, comparisons of lower body joint kinematics during real-world exposure to slip hazards and virtually generated slip hazards during overground walking have not been performed. The current study was unique due to the fact that it utilized an exact replica virtual environment of the laboratory used for data collection, promoting the most realistic immersion possible.

The findings of the current study revealed no significant differences in knee and ankle joint kinematics of the slipping leg when exposed to real-world and virtually generated slip hazards. Previous literature has demonstrated the effectiveness of using VR for locomotor rehabilitation and balance training following a stroke [22,42]. In addition, VR has been shown to be effective in improving reaction time in the elderly when exposed to various slip contaminants [33]. However, while previous studies have assessed gait characteristics and lower extremity joint kinematics while immersed in a VR environment while walking on a treadmill [43,44], no studies have assessed lower extremity joint kinematics during overground walking while immersed in a VR environment that is an exact replica of the physical environment, further adding to the uniqueness of the current study. Similar to Chan et al. [43], who compared lower extremity joint kinematics between a real environment and virtual environment during treadmill walking, the current study did not reveal any significant differences in knee or ankle joint kinematics during overground walking between the REAL and VR environmental conditions. The lack of significant differences may be due to the similarities between environments. Additionally, previous literature has shown differences in gait biomechanics when a slip contaminant is expected compared to when it is unexpected [45]. However, the current study did not reveal any significant differences between unexpected slip hazard exposure and expected slip hazard exposure. Previous literature has shown that gait kinematics are often preserved when exposed to various slip events when wearing slip-resistant shoes [46]. Therefore, the participants' use of slip-resistant shoes during gait trials is a possible explanation for the preservation of gait kinematics when exposed to slip hazards.

Additionally, this study attempted to determine the effects VR exposure may have on dynamic postural stability by using several TUG variations. The results revealed significantly improved TUG-C scores after being exposed to slip hazards in a VR environment. Primarily, TUG is used in clinical settings and involves a certain amount of dynamic postural stability, often used to determine fall risk in a diseased population and the elderly [47]. However, TUG-C and TUG-M have been recently used in research settings due to the dual-task nature associated with each variation, suggesting a greater real-world application compared to the standard TUG [48]. Because of the variability of occupational environments, the increased complexity of the TUG-C and TUG-M seem to be more reliable than the standard TUG for assessing dynamic postural stability for occupational populations. Additionally, the current results demonstrated longer times to completion during TUG-C when compared to TUG-S and TUG-M, suggesting the significant role of the higher centers during human locomotion and the potential of TUG-C to be used to detect cognitive disabilities more effectively than TUG-S and TUG-M [49]. Additionally, previous literature has explored the idea of the role of virtual reality in cortical reorganization. Due to the potential of realistic environmental exposure of immersive VR, spatial navigation has been shown to be significantly improved following a 4-week training protocol using VR [50]. Although the mechanism is relatively unknown, data seem to suggest a significant relationship between greater prefrontal cortex function and spatial navigation. In stroke patients, bilateral prefrontal cortex activation occurs and promotes effective modulation of motor commands when exposed to events causing postural instability during virtual reality immersion [51]. Given the essential role of the prefrontal cortex during locomotion, exposure to VR may play a crucial role in efficient gait modulation and effective environmental navigation. Greater prefrontal recruitment and cortical reorganization may explain the improved TUG-C scores following VR exposure.

Finally, in the current study, exposure to VR did not result in an increased SSQ score, further suggesting the minimal negative effects of VR exposure on overall function (i.e., vision, nausea, dizziness, etc.). Exposure to various immersive interfaces can cause sickness symptoms. Because these symptoms may impact other dependent variables, it is critical to monitor such symptoms. SSQ is commonly used to do this and has been validated throughout the years [34,35]. Previous literature has shown that symptoms such as nausea, dizziness, and vertigo can be dangerous in some conditions [52]. Furthermore, as a result, the overall time of exposure may be limited and thus hinder appropriate adaptation and motor learning for obstacle avoidance in hazardous situations [53]. Although prolonged exposure to VR can keep individuals motivated and engaged, it may be counterproductive and harmful based on the increased possibility of simulator sickness. However, guidelines exist that are intended to reduce the risk of simulator sickness such as field of view, duration, latency, acceleration, and navigation speed [54]. Simulator sickness is highly dependent on the duration of exposure, and experience in VR immersion and should be controlled without impacting adaptation to certain stimuli [55]. The results of the current study did not show any significant increases in simulator sickness following acute exposure to VR, which may be due to the acute and short-term immersion in the VR environment. Previous literature suggests that in order to ensure effective adaptation while minimizing simulator sickness, VR exposure should be short term and involve interval experiences [56]. Therefore, repeated acute exposure to various occupational risks while immersed in VR environments may be effective in promoting fall prevention strategies in occupational environments.

Recent literature has explained the effectiveness of using VR while walking on a treadmill while immersed in VR [57]. Although specific for the elderly, results from this study demonstrated an improvement in mobility and cognitive function [57]. Therefore, it is reasonable to assume that an intervention involving repeated exposure to fall risk hazards while immersed in VR as a means for fall prevention training may be effective in occupational populations. However, it has been shown that adaptation that occurs during treadmill walking does not transfer to overground walking due to the variability and

modulation of locomotor patterns and differences in gait kinematics, kinetics, and myoelectric activity in the lower extremity musculature during overground walking compared to treadmill walking [58–60]. Therefore, repeated exposure to uneven surfaces and various fall risk hazards during overground walking could be critical in promoting proper adaptation and transferability [61,62], thus being effective in recruiting neural circuits and achieving desirable outcomes at the functional level [63]. Previous literature has shown visual experience and action may be significant to functional recovery of vestibular disorders and stroke. This visual experience with VR provides efficient reorganization of sensorimotor circuits and allows individuals to adjust the body's center of mass [64]. Overall, the results of the current study suggest the potential effectiveness of VR as a potential strategy that may be utilized in fall prevention training for various populations. Although often used for stroke patients, VR is a feasible option and provides unique advantages in training programs for fall prevention due to the lower pricing and portability of VR compared to traditional options. Because of the lack of significant differences in lower extremity joint kinematics between environmental conditions, the data suggest that gait characteristics, when exposed to slip hazards, both in real-world and virtual environments, are similar and may allow for effective motor learning and adaptation to fall risk hazards.

5. Conclusions

The current study suggests the potential benefits of using VR for fall prevention training based on the similarities in lower extremity joint kinematics during REAL and VR environmental conditions, as well as similar SSQ scores after VR exposure and improved TUG-C scores. Therefore, repeated exposure to slip events using repeated acute VR immersion to expose individuals to fall-risk hazards without real-world injury risk may promote improvements in anticipatory changes in the environment, potentially promoting reactive adaptations and ultimately improving postural recovery in response to perturbations and reducing fall-related injuries and fatalities as a result of slip events [65]. The current study uniquely compared lower extremity joint kinematics of the slipping leg during real-world exposure and virtually generated exposure to slip hazards during overground walking. Short-term repeated exposure to VR may promote greater sensorimotor transformations of visual input, ultimately resulting in an individual being able to more effectively adapt to uneven terrain and fall risk hazards. However, further research is required and should focus on exposure to various types of slip and trip hazards during overground walking when exposed to VR environments, focusing on the neuromuscular skills required for slip and trip recovery during locomotion.

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