

Article

The Effects of an Acute Exposure of Virtual vs. Real Slip and Trip Perturbations on Postural Control

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Abstract

Background: Current methods of postural control assessments and interventions to improve postural stability and thereby prevent falls often fail to incorporate the hazardous perturbation situations that frequently accompany falls. Virtual environments can safely incorporate these hazards. The purpose of the study was to identify if virtual slip and trip perturbations can be used as an exposure paradigm in place of real slip and trip perturbations to improve postural control. **Methods:** Fifteen healthy young adults were included in this study. Two paradigms, real gait exposure (real) and virtual environment gait exposure (virtual), consisting of real and virtual slip and trip trials, were performed by each participant in a counterbalanced order to avoid order effects. At baseline and following real and virtual paradigms, the modified clinical test for sensory integration and balance (mCTSIB), limits of stability (LOS), and single-leg stance (SLS) using BTracks balance plate were administered. Separate one-way (baseline vs. Real vs. Virtual) repeated measures analysis of variance were conducted on response variables. **Results:** In the posterior left quadrant of the LOS, significant differences were found after the real paradigm compared to baseline ($p = 0.04$). For the anterior left quadrant and total LOS, significant differences post real paradigm ($p = 0.002$ and $p < 0.001$) and virtual paradigm ($p = 0.007$ and $p < 0.001$) compared to baseline were observed. For the SLS, the left-leg significant differences were observed post real paradigm ($p = 0.019$) and virtual paradigm ($p = 0.009$) compared to BL in path length, while significant main effects were found for mean sway velocity for the left leg only ($p = 0.004$). For the right leg, significant differences were only observed after the virtual paradigm ($p = 0.01$) compared to BL. **Conclusions:** Both virtual and real paradigms were identified to improve postural control. The virtual paradigm led to increased postural control in the right-leg SLS condition, while the real paradigm did not, without any adverse effects. Findings suggest virtual reality perturbation exposure acutely improves postural control ability compared to baseline among healthy young adults.

Keywords: virtual reality; postural stability; slips; trips; postural perturbation



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1. Introduction

Postural equilibrium and postural orientation are critical components of human movement that play a significant role in daily activities, mobility, and work tasks. Impairments in balance and gait can lead to fall related injuries and deaths. Such falls and fall-related

injuries are common among individuals with an elevated fall risk, such as older adults, high-risk occupational populations such as construction workers and roofers, and individuals with neurological disorders [1–4]. Not only are falls a threat to public health, but they also impact the economy on a large scale. Over USD 50 billion is spent via Medicare, Medicaid, private health insurance, and out-of-pocket payments on medical expenses due to fall-related injuries each year in the United States for those over the age of 65 alone [5]. Currently, the primary forms of interventions to improve postural control and reduce fall risk include resistance training, aerobic exercise, adapted physical activity, tai chi, wobble board, stability ball, and general balance training [6].

Virtual reality (VR) has gained popularity as an innovative tool for improving balance and gait [7–11]. Virtual environments (VEs) have been effective in improving balance and gait by creating immersive simulations that replicate real-world activities and movements. One advantage of VEs is that potentially hazardous situations that are likely to cause fall-related injuries in real-world environments can be simulated without any actual danger. However, VR immersions have been reported to cause acute postural control deficits immediately post immersion [12–16], though these results are mixed [17,18]. Postural adjustments are made by the body during ambulation and activities based off afferent feedback from the somatosensory, vestibular, and visual systems. During VR immersion, balance may be compromised due to the discrepancy between the sensory inputs provided by the VR environment and those provided by real-world environments [15,18–20]. These discrepancies have often been associated with vergence and accommodation conflicts as well as visual–vestibular sensory conflicts [19].

Advances in the technology of head-mounted devices (HMD) allow for drastically improved quality of VEs [21,22]. The quality of virtual reality immersions is significant not only in reducing potential symptoms, but it can also affect presence, which is a measure of how immersed one feels and the realism within a virtual environment [21,22]. VR simulations may not always accurately replicate the sensory feedback that individuals receive during real-world movements. Common interventions utilizing VR for postural control and gait improvement include treadmill training and utilizing the Nintendo Wii or Bru systems [10,23–26]. These interventions do not utilize the added benefit of ambulation and autonomy seen with HMDs. To date, if training utilizes HMDs, then postural perturbations are either absent or are not replicates of real-world obstacles [25,27,28]. Hence, an analysis of VR-generated postural perturbations such as slip and trip hazards in postural control training is warranted.

The effects of real slip and trip perturbations and exact VR replicas of these perturbations on postural control have not yet been compared. In order to assess the feasibility of utilization of VR for fall risk prevention, the acute effects on postural control should be evaluated. The purpose of this study was to assess the acute effects of two testing paradigms, namely the real gait exposure (real) and virtual environment gait exposure (virtual), on postural control. The secondary aim of this study was to compare real to virtual exposure paradigms in attempts to infer the efficacy of a customized VR fall prevention exposure tool that incorporates virtual slip and trip hazards. The authors hypothesize that both real and virtual perturbances will significantly affect participants' postural control similarly.

2. Materials and Methods

2.1. Participants

This study was approved by the Mississippi State University's Institutional Review Board (Protocol #21-248). A total of 15 healthy young adults (8 females, 7 males, age 23 ± 3.31 years) without any self-reported history of neurological, musculoskeletal, cardio-

vascular, or vestibular disorders were recruited for the study. All participants included indicated an above recreationally trained fitness status, which is defined as 3–4 days/week with consistent anaerobic and aerobic activities for the last three months. All participants were recruited through flyers, emails, and announcements. Informed consent was obtained from all participants. To confirm physical fitness status, participants also filled out a physical activity readiness questionnaire to ensure no health-related complications were present. Upon completion of these forms, participants were cleared for data collection. A summary of the anthropometric data can be found in Table 1.

Table 1. Anthropometric Data for all Participants.

Variable	Mean	STD
Age (years)	23.46	3.31
Height (cm)	173.85	8.46
Weight (N)	806	111.89
Shoe Size (U.S. men's)	9.03	2.71

2.2. Equipment

All experimental procedures were conducted in the University's Neuromechanics Laboratory. Balance assessments were performed using the Balance Tracking Systems (BTrackS) (Balance Tracking Systems, Inc., San Diego, CA, USA) portable force plate, which has the capability for different posturographic balance assessments and is packaged with the applicable software. The Assess Software version 7.5.4. was used in this study. The BTrackS assess balance software (version 7.5) can quantify center of pressure (COP) excursions during bipedal [29] and unipedal [30] stances. The plate has been concurrently validated against other laboratory-grade force plates (AMTI OPT 464508) [31]. For VR immersion, the HTC Vive Pro (HTC America, Inc. Seattle, WA, USA) head-mounted display was used. The virtual lab environment was developed using a Lidar scan of the Neuromechanics lab and run within Unity 3D software (version 2021). A comparison of the virtual and actual environments can be seen in Figure 1.



Figure 1. Real environment (left) and virtual environment (right).

2.3. Postural Control Assessment Battery

A battery of postural control assessments was collected as the response variables in the study. This battery consisted of the modified Clinical Sensory Integration on Balance (mCTSIB), limits of stability (LOS), and single-leg stance (SLS). This battery assesses sensory contributions to static bilateral and unilateral postural control as well as functional base of support in postural control. Each of the following postural control assessments was performed once during each instance of data collection.

mCTSIB: Participants were asked to stand as still as possible on the BTrackS plate with a bipedal stance during four different conditions: eyes open (EO), eyes closed (EC),

eyes open on a foam surface (EOF), and eyes closed on a foam surface (ECF). Participants stood for twenty seconds within each condition. Each condition was performed only once. The duration of each condition was 20 s. Participants stepped off the board while the experiment team prepared the board and software for the subsequent test condition. The entire test takes about 3–5 min to complete. The mCTSIB is widely used to assess sensory contributions to balance and has demonstrated high test–retest reliability and validity [32]. The four conditions utilize both simultaneous use and isolated use of each of each afferent sensory feedback pathway as it pertains to balance.

LOS: Participants were asked to stand with their feet shoulder-width apart on the plate. While keeping their feet fixed to the plate, they leaned in all directions as far as possible without falling or stepping off the plate. Subjects performed this task until they felt as though they could no longer displace their COP any further in any direction. Data were recorded relative to an origin point set at the point where the individual's net COP is located during quiet standing. Live biofeedback was available during this test to allow individuals the ability to track their COP manipulation. BTrackS LOS has previously been shown to be a reliable test of volitional postural control [33].

SLS: Participants were asked to stand with hands on hips and with one foot in the center of the balance plate. Just prior to trial initiation, participants lifted their other leg off the ground to a 90-degree knee flexion. This position was held with the goal of minimal movement for the duration of the trial. Participants performed two 20 s trials for each leg.

2.4. Experimental Procedures

This study was a two-day data collection protocol, with the first day consisting of collecting informed consent and anthropometrics as well as the familiarization and the baseline (baseline) postural control assessment batteries. This lasted approximately 30 min. The second day of data collection consisted of 28 total gait trials. These trials were split into two conditions: real gait exposure (real) and virtual environment gait exposure (virtual) paradigms. During trials, participants were first harnessed in a ceiling mounted safety harness to prevent any undue falls and were then instructed to walk at a normal self-selected pace across a platform. Self-selected walking speeds were used to ensure natural gait mechanics and to reduce movement patterns that could influence postural responses. Both conditions consisted of 10 normal gait trials, with an additional unexpected slip, unexpected trip, expected slip, and expected trip trials. Participants were told to face their back to the walkway until instructed to turn and begin walking, during which time the experimenters prepared the walkway accordingly for each trial. Durations between trials were standardized to 20 s to allow preparation. In the real paradigm, slips were induced by applying a 75% glycerol and 25% water mixture to the walkway, while trips were induced by placing a wooden block directly in the participant's path prior to each respective trial. For the virtual paradigm, a virtual replication of both slips and trips hazards was generated in the same spatial position as the perturbations in the real paradigm. In unexpected trials, participants were not warned of the slip or trip perturbations, while in the expected trials, they were. The unexpected trials were merely with no prior notification to the participant, but they could still identify a slip or trip hazard during their gait to emphasize their compensatory postural mechanisms, whereas the expected trials involved participants being told of an upcoming slip or trip hazard in their pathway during gait to emphasize anticipatory postural mechanisms. After each condition was completed, the postural control assessment battery was immediately collected. The second day of data collection lasted approximately two hours and marked the end of the data collection.

Participants performed both the real and virtual paradigms with the order counterbalanced to avoid any potential order effects. The inclusion of both expected and unexpected

perturbations was important for assessing participants' adaptive responses to both anticipated and non-anticipated balance disturbances, which are important in fall prevention research. The real and virtual slip and trip hazards that provide postural perturbations were attempted to resemble small puddles and small obstacles, respectively, that can be presented in the real world. In the clinical context, gait and balance training involves a multi-modal approach with physical therapist often incorporating a variety of treatment strategies aimed at challenging all three balance systems (visual, vestibular, and proprioceptive). The virtual environment presents postural perturbational challenge to these systems, specifically the visual system, that can be beneficial for balance and gait rehabilitation.

2.5. Data Analysis

For the mCTSIB, the postural sway outcome variables used for analysis were center of pressure (COP) path length, measured in cm and 95% ellipse area width and length. COP path length is measured at successive time points with the following formula: $\text{COP path length} = ((\text{COP}_{x2} - \text{COP}_{x1})^2 + (\text{COP}_{y2} - \text{COP}_{y1})^2)^{0.5}$, where COP_{x2} and COP_{x1} are adjacent time points in medial/lateral space, and COP_{y2} and COP_{y1} are adjoining time points in the anterior/posterior space. Larger COP path length indicates less static control of posture. The 95% ellipse length and width includes the most proximal 95% of COP path length data from the average COP position. Larger height and width of 95% ellipse area represents decreased postural control ability. For the SLS, response variables included COP path length and mean sway velocity. Mean sway velocity was calculated by dividing a given trial's COP path length by the duration of the trial. Each SLS protocol consists of two left-leg and two right-leg trials. Thus, the average sway velocity of each respective leg was used for analysis at each timepoint. For the LOS, the response variables are total area of base of support (BOS), along with four directional quadrants, including anterior left (AL), anterior right (AR), posterior left (PL), and posterior right (PR). Total area traversed from the quiet standing origin, recorded in cm^2 , is a measure of total functional BOS.

2.6. Statistical Analysis

Separate one-way (baseline vs. real vs. virtual) repeated measures analysis of variance (RM-ANOVA) were conducted for all response variables. In the case of significant main effects, all RM-ANOVA tests satisfied the assumptions of sphericity; thus, LSD was used for pairwise comparisons post hoc. Alpha was set to a significance level of 0.05 prior to evaluation. All analysis was performed in IBM SPSS (version 29).

3. Results

mCTSIB: The COP total path length, 95% ellipse width, and 95% ellipse length was evaluated independently for each condition of the mCTSIB. No significant main effects for EO, EC, EOF, and ECF were observed (Figures 2–4).

LOS: Significant main effects were found in the PL ($p = 0.04$) and AL ($p = 0.01$) quadrants along with total score ($p < 0.001$). For the PL quadrant, pairwise comparisons revealed significant increases in area post real paradigm compared to baseline ($p = 0.04$). The AL and total score showed significantly greater LOS area post real paradigm compared to baseline ($p = 0.002$ and $p < 0.001$, respectively) as well as the virtual paradigm compared to baseline ($p = 0.007$ and $p < 0.001$, respectively) (Figure 5).

SLS: Significant main effects were found for COP path length for the left ($p = 0.006$) and right leg ($p = 0.042$). For the left leg, pairwise comparisons showed significant decreases in average pathlength in the real paradigm ($p = 0.019$) and virtual paradigm ($p = 0.009$) compared to baseline. For the right leg, pairwise comparisons revealed that only the virtual paradigm ($p = 0.01$) caused significant decreases in average pathlength compared

to baseline (Figure 6). Significant main effects were found for mean sway velocity for the left leg only ($p = 0.004$). Pairwise comparisons revealed significant decreases in mean sway velocity in the virtual paradigm ($p = 0.002$) compared to baseline (Figure 7). No significant differences were found on the differences or symmetry index.

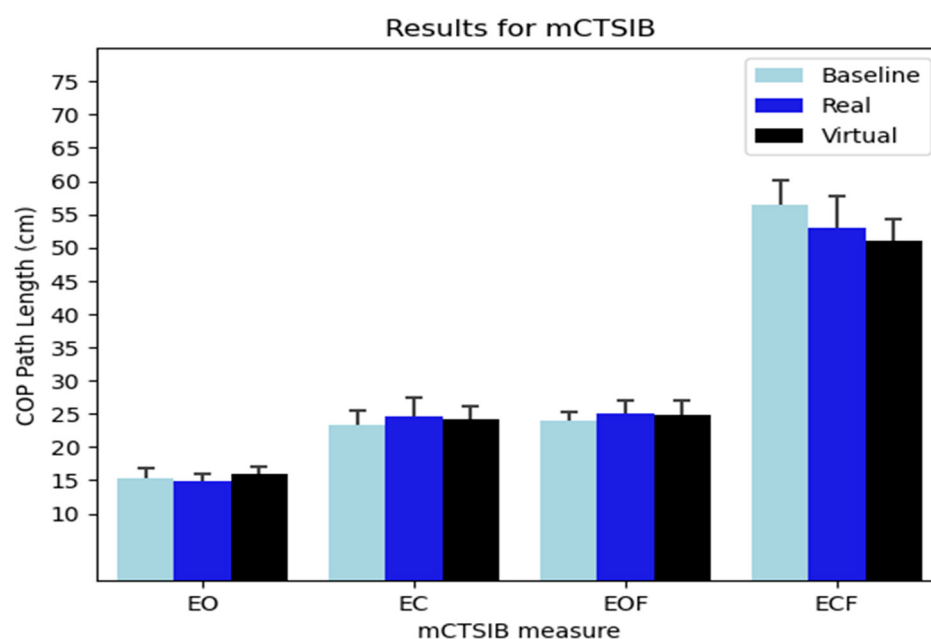


Figure 2. Center of pressure (COP) for eyes open (EO), eyes closed (EC), eyes open foam (EOF), and eyes closed foam (ECF) conditions of the mCTSIB during baseline, real, and virtual paradigms.

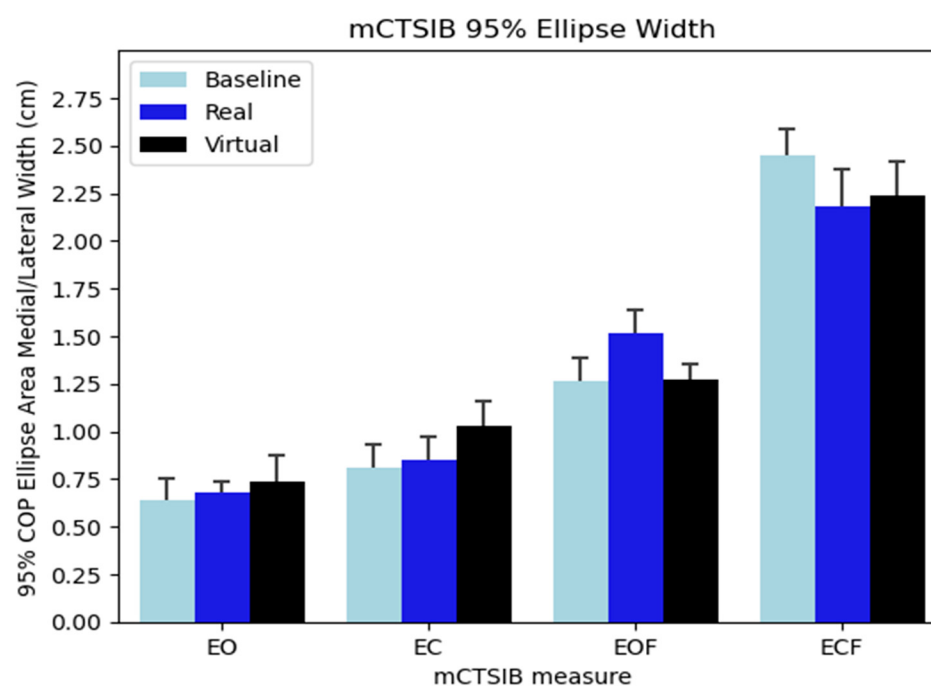


Figure 3. The 95% COP ellipse width for eyes open (EO), eyes closed (EC), eyes open foam (EOF), and eyes closed foam (ECF) conditions of the mCTSIB during baseline, real, and virtual paradigms.

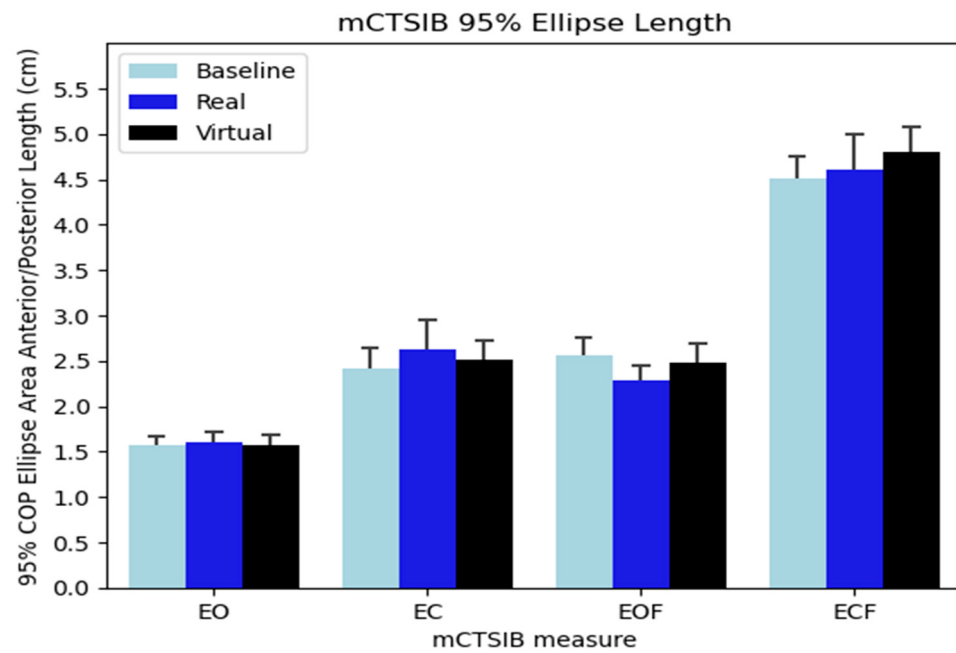


Figure 4. The 95% COP ellipse length for eyes open (EO), eyes closed (EC), eyes open foam (EOF), and eyes closed foam (ECF) conditions of the mCTSIB during baseline, real, and virtual paradigms.

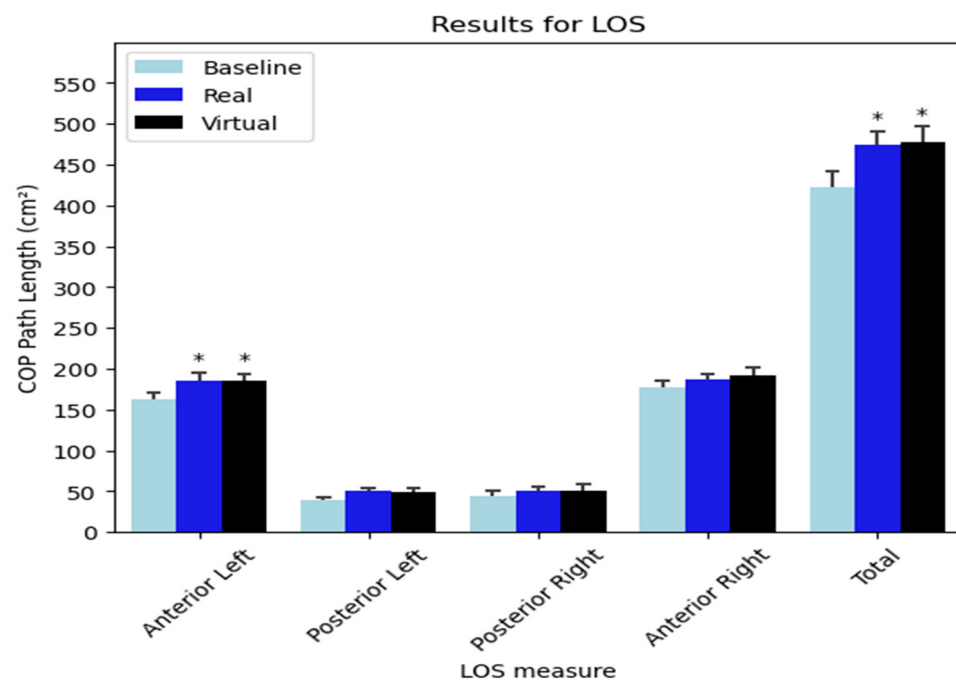


Figure 5. LOS functional BOS area for total and quadrants during baseline, real, and virtual paradigms. Significant differences of $p < 0.05$ from baseline are indicated with *.

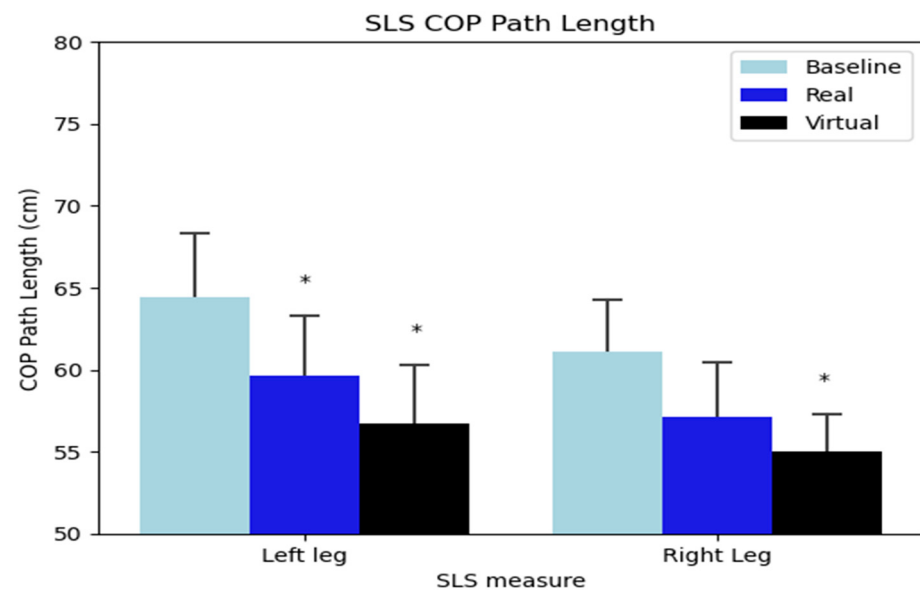


Figure 6. SLS COP path length for both left and right legs during baseline, real, and virtual paradigms. Significant differences of $p < 0.05$ from baseline are indicated with *.

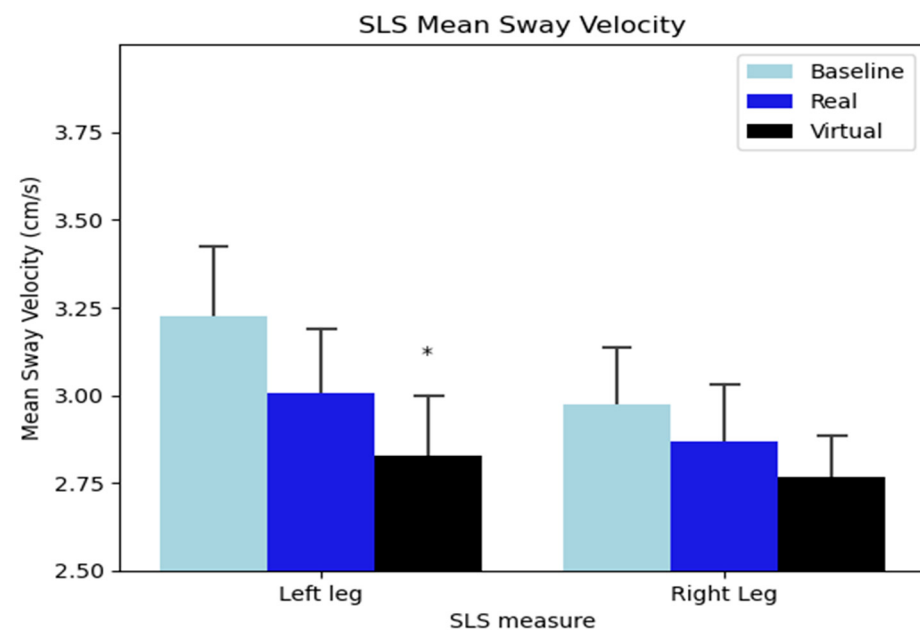


Figure 7. SLS mean sway velocity for both left and right legs during baseline, real, and virtual paradigms. Significant differences of $p < 0.05$ from baseline are indicated with *.

4. Discussion

This study compared the acute effects of using unexpected and expected slip and trip perturbations in the real and virtual paradigms compared to baseline. Postural stability and sensory pathway utilization during quiet standing, as measured with the mCTSIB, was not significantly affected by either the real or virtual paradigms. This finding contrasts with the previous literature where VR intervention training and traditional balance training yielded improvement in mCTSIB scores. Of note, there is a common trend of prolonged, repetitive exposure to VR training environment and significant improvements in mCTSIB assessments [34,35]. The functional BOS of participants measured with the LOS significantly improved from baseline to post real and virtual paradigms. For SLS, there were significant decreases in average COP path length in the left leg as a result of the real and virtual paradigms and specifically with the virtual paradigm for mean sway velocity. For the

right leg, significant decreases in average COP path length were only observed after the virtual paradigm. This finding suggests that the virtual paradigm may be superior to improving postural control over the real paradigm. These findings also align with the previous literature where VR interventions were reported to improve SLS duration in healthy and Parkinson's disease patients [36]. While improvements in postural control were identified after the virtual paradigm, these findings are limited to healthy young adults, and findings may be different for clinical or elderly populations. However, the current findings support the previous literature reporting that VR training can improve postural control even among healthy young adults [9,37,38].

In examining the trends seen with the mCTSIB, increased mean COP path length in the EO condition and decreased COP path length in the ECF condition were observed post virtual paradigm. EO utilizes all three sensory feedback pathways of the proprioceptive system. ECF isolates vestibular contribution to postural control by occluding the visual and manipulating the proprioceptive pathways with conflicting sensory information [32]. Lower COP path length indicates better postural control. It has been suggested that during VR immersion, the human postural control system relies less on the visual system and more on the vestibular system. This adaptation is proposed to be an adaptation of the visual-vestibular conflict experienced during immersion [18]. However, with a lack of statistically significant differences, further investigation on this phenomenon is much warranted.

An improvement in the LOS scores from the baseline paradigm, particularly in the left quadrants, was evident. The increased functional BOS seen in this study could be attributed to multiple factors, such as improved postural control as a result of the real and virtual paradigms. More likely, however, it may have been a product of the learning effect seen with the BTrackS LOS protocol. Indeed, it was established that at least one trial of the LOS protocol is needed before establishing consistent intraparticipant results [33]. The similarity in results seen after both the real and virtual paradigms would indicate that the functional base of support was either improved by both paradigms or neither compared to baseline or was not a result of motor learning. The key inference to make in this case is that there were no significant differences seen as a product of specific paradigms. The SLS protocol, however, has a practice trial embedded within the protocol to avoid familiarization effects [30]. The significant differences in pathlength immediately post real paradigm for the left leg and immediately post virtual paradigm for both legs cannot be explained due to learning effects. This suggests that both the real and virtual paradigms could be used as a method of improving SLS as a measure of dynamic postural control, with virtual being the preferable method, as symmetry and total pathlength were lower immediately following VR trials.

The acute improvements from the virtual paradigm in this study do not imply long-term improvements. The longitudinal effects of the virtual paradigm individually and in comparison to the real paradigm on postural control should be examined before drawing inference. That is, a study design that utilized follow-up tests after a retention period of no training would isolate whether the results seen in this study persist in a relatively permanent manner. Another limitation includes the participant's ability to identify perturbations prior to the slip or trip trial. Better methods for masking these perturbations to obtain a true measure of "unexpected" should be explored in future research. While the acute effects of both these exposure paradigms are established here, future studies should evaluate individual groups and the long-term training effect of the virtual paradigm, examining long-term exposure to virtual postural perturbation training as well as adaptations to the sensory conflicts associated with VR immersions in comparison to the current methods used for postural control training in various populations. Additionally, there are a number

of limitations with the assessment protocols used in this study. With respect to trial durations, using 20 s trials for COP path length data collections has recently been put under scrutiny. Investigators have noted that collections lasting 30 s require fewer trials to collect reliable data [39] than the use of 20 s trials. Further, trials of durations between 90–120 s are necessary to achieve excellent levels of test–retest reliability [40,41]. With respect to the use of COP path length as an outcome variable, the literature suggests that path length alone lacks the directional nature of sway and does not include a temporal component of sway. It has also been shown to be a more sensitive and reliable measure of postural control [40–43].

5. Conclusions

This initial study explores the impact of an acute exposure to real and virtual testing paradigms, which included slip–trip postural perturbations, on postural control. Both the real and virtual exposures to such testing paradigms elicited significant acute improvements in the postural control system. However, the virtual testing paradigm elicited acute improvement in some postural control assessments, specifically the SLS protocol, that the real testing paradigm did not. The findings suggest that VR-based perturbations can impact postural control positively, and much research is warranted to assess if such VR-based training, when imparted for a longer time, can induce both immediate and long-term postural adaptations.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of Mississippi State University (IRB Protocol #21-248) on 28 November 2022.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study based on the study approved by the Institutional Review Board of Mississippi State University (IRB Protocol #21-248) on 28 November 2022.

Data Availability Statement: Averaged sample data is provided within the manuscript. Further inquiries can be directed to the corresponding author.

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Conflicts of Interest: The authors declare no conflicts of interest.

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