

Effects of Perturbation-Based Slip Training Using a Virtual Reality Environment on Slip-induced Falls

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Abstract—The purpose of the current study was to design and evaluate the effectiveness of virtual reality training in improving recovery reactions and reducing fall frequency in older adults. Twenty-four older adults were recruited and randomly assigned to two groups (virtual reality training and control). Both groups underwent three sessions including baseline slip, training and transfer of training on slippery surface. Both groups experienced two slips, one during baseline and the other during the transfer of training trial. The training group underwent 12 simulated slips using a visual perturbation induced by tilting a virtual reality scene while walking on the treadmill and the control group performed normal walking during the training session. Kinematic and kinetic data were collected during all the sessions. Results demonstrated a reduced incidence of falls in the training group during the transfer of training trial as compared to the control group. The training group was able to transfer reactive control strategies learned during training to the second slip trial. The reactive adjustments included reduced slip distance. Additionally, gait parameters reflective of gait instability (stride length, step width, variability in stride velocity) reduced after walking in the VR environment for 15–20 min. The results indicated a beneficial effect of the virtual reality training in reducing slip severity and recovery kinematics in healthy older adults.

Keywords—Falls, Elderly, Biomechanics, Fall prevention training, Virtual reality.

INTRODUCTION

Fall prevention in older adults has been a focus of many researchers due to a constant increase in injuries and fatalities in the past decade. Slip-induced falls account for 87% of all hip fractures, leading to a loss of

functional independence and increase in fear for future falls in older adults >65 years.²⁰ Existing proactive intervention strategies for older adults (i.e., strength, endurance, balance training) have produced mixed results on the success of these exercise programs in terms of reducing fall accidents.^{7,14} One of the reasons for the inconsistency in the effect of the existing exercises on reducing falls may be that they do not specifically target the neuromuscular skills required for fall prevention.

A training program that helps older adults learn movements directly related to recovery responses may improve their sensory and muscle co-ordination and thus their ability to recover from a slip-induced fall. A specific training regime that has a structural similarity with slip-induced fall is repeated perturbation training. Recently, Bhatt *et al.*¹ demonstrated improved recovery (i.e., reactive adaptations) in young adults after repeated exposure to a simulated slip-perturbation. Similarly, Pai *et al.*¹⁸ reported that older adults were able to reduce the incidence of backward loss of balance through adaptations to repeated slips induced during sit-to-stand. Such adaptations can be attributed to the anticipatory changes (i.e., proactive adaptations). These findings suggest a potential application of repeated perturbation training as a slip recovery intervention for the elderly.

There is an emerging use of virtual reality (VR) environments to study various aspects of human balance and control.^{5,9,16} VR is an excellent medium to produce simulated, interactive, and multi-dimensional environments on a desktop monitor or on a Head Mounted Display (HMD). One of the major advantages of using VR is that individuals can be presented with challenging but safe and varied environments, while maintaining control over stimulus delivery and measurement.²¹ The use of VR in balance rehabilita-

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tion follows the principle of ego-motion which states that changing VR environments induces a visual-vestibular sensory conflict, thus perturbing the natural stance requiring corrective action taken by the body to maintain balance.⁶

Recently, VR environments were used to study fall risk in older adults.⁴ It was found that visual motion induced postural response in the older adults and they responded more strongly compared to younger counterparts. A general training effect with less stepping responses and improved ability to balance was observed with repeated exposure to VR-induced sensory conflicts in older adults.³ Walking in the VR environment reduced stride lengths, increased step widths, and increased variability in stride velocity in younger adults.⁵ However, there is lack of studies examining gait variability in older adults while walking in the VR environment.

Numerous studies have suggested using VR training in fall prevention programs as it may induce goal directed practice.^{5,9,16} However, no current VR training is available that aims to improve recovery reactions in older adults. There is a need to develop a VR training program specific to slip-induced falls, and evaluate if it can be transferred to an actual slippery surface. There is also a need to elucidate the biomechanical and neuromuscular mechanisms used by the older adults to recover when exposed to such VR perturbations. Additionally, there is a need to understand the effects of VR environment on gait variability in older adults.

The objectives of the study were: (1) to design a virtual reality training to induce perturbation similar to a slip and to evaluate the effect of virtual reality training in improving proactive and reactive responses in older adults when exposed to an actual slippery surface; (2) to quantify the biomechanical changes during the VR training trials; and (3) to compare gait variability between normal treadmill walking and VR treadmill walking.

MATERIALS AND METHODS

Participants

Twenty-four healthy older adults (>65 years, 12 male, and 12 female) were recruited for the study from the local community. The sample size was

estimated using power analysis on preliminary test results. The preliminary study involved four older adults going through VR perturbation training protocol and a subsequently test on the slippery surface. The slip distance, as a primary parameter of interest in slip biomechanics, was used to calculate the statistical power for this study. The participants' demographics are presented in Table 1. Written consent form approved by local Institutional Review Board (IRB) was obtained from the participants before participation. Participants were divided into a control group ($n = 12$), and a virtual reality training (VRT) group ($n = 12$).

Prior to testing, each participant completed a visual acuity test (i.e., Snellen's chart) and a questionnaire on the symptoms of cyber sickness using the Simulator Sickness Questionnaire (SSQ).⁸ The SSQ score was collected at three instances (before training, after training, and the next day of training) to evaluate presence of dizziness after being in the virtual environment.

Apparatus

The virtual reality training was conducted on an instrumented treadmill (Nordick, T7 si, NY, USA). The virtual reality scene was rendered on a head mounted display (Glasstron LDI-100B Sony, with a 28° horizontal field of view in each eye) (Fig. 1). The HMD had two 0.7-inch liquid crystal display screens whose images combine to give the effect of viewing a 30-inch screen 1.2 m away. The HMD was lightweight (120 mg) and had a resolution of 832(H) × 624(V). Foam blinders attached to the HMD blocked any peripheral vision of the external environment. A regular downtown VR scene was generated (Fig. 2) with buildings, light poles, road, pavement, street signs, etc. Software synchronizing the hardware drivers and generating graphics were written in C/C++/OpenGL. The frame rate of the scene was set at 64 Hz. A tracker was attached to the HMD (Fastrak, Polhemus, VT, USA), which allowed participants to rotate their head and feel the virtual environment in all directions (6 dof-X, Y, Z, pitch, yaw, and roll). The tracker had a 120 Hz update rate with adjustable motion prediction.

TABLE 1. Participant demographics (Mean ± SD).

	Group		<i>p</i> value
	Control ($n = 12$)	Training ($n = 12$)	
Age (years)	74.18 ± 5.82	70.54 ± 6.63	0.86
Mass (kg)	69.63 ± 9.45	67.77 ± 8.04	0.99
Stature (cm)	169.41 ± 9.16	167.13 ± 11.52	0.98

The *p* value represents the results of a *t* test comparing two-groups.

The virtual slip consisted of perturbations (tilts) in the pitch plane of the VR scene at random intervals (approximately 10–20 s apart). The laboratory lights were turned off during the training trials.

A standardized protocol^{11,12} for slip and fall research was implemented. Briefly, unexpected slips were introduced by having the participants walk over a slippery surface covered with a 1:1 water and KY-Jelly mixture (dynamic COF = 0.12).

A six-camera motion capture system (Qualisys) was used to record full-body kinematic data at 100 Hz. Twenty-four reflective markers were attached to various bony landmarks of the body (head, ear, shoulder, acromion, elbow, wrist, knuckle, anterior superior iliac spine (ASIS), knee, ankle, toe, heel, trunk (L5/S1 segment)). The marker configuration was similar to the previous studies.¹³ Kinetic data were collected at

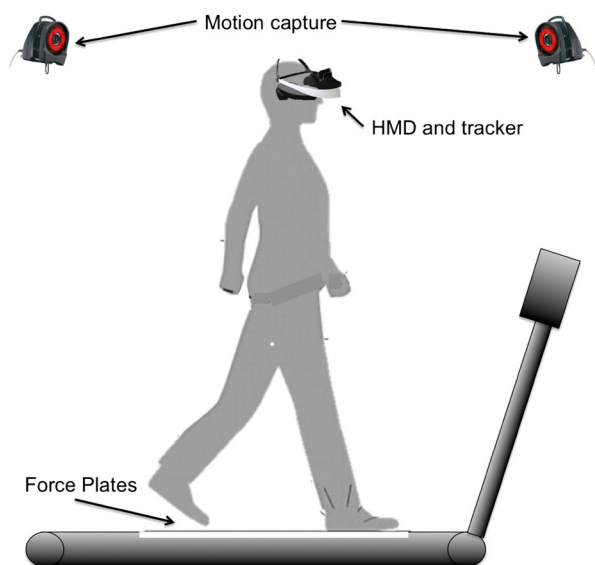


FIGURE 1. Experimental set-up of the virtual reality training including the treadmill and the head mounted display (HMD) along with the tracker and the motion capture system.



FIGURE 2. Virtual scene displayed on the head mounted display (the flow speed was matched to the speed of the treadmill).

1,000 Hz from the force plates on the walkway. Participants wore a full body custom-made fall-arresting harness throughout the experiment.¹³ Uniform sleeveless shirts and shorts, and athletic shoes were provided to all participants to minimize loose clothing and shoe-sole differences.

Protocol

The study comprised of three sessions: baseline measure, training acquisition, and transfer of training, on three separate days (Fig. 3). All participants underwent a slip trial on the slippery floor surface that served as a baseline measure (Slip1) during the first session. After 2 weeks (to minimize the memory effect of the slip protocol), the training group performed the virtual reality training on the treadmill and the control group performed normal walking trials on the walkway. During the third session, both groups were exposed to a slippery floor surface similar to the baseline session (Slip2).

Session 1 (Baseline Measure)

After attaching the markers, participants were instructed to walk on the walkway for 10 min at a self-selected pace to get them familiarized with the harness and the lab environment. A metronome was used to record participants' self-selected pace (which was then used to regulate the pace in subsequent sessions). The baseline kinematic and kinetic data were recorded from five normal walking trials before inducing the slip. A walking trial contains 5 s measurements, approximately 2–3 complete steps. After collecting the normal walking trial, an actual slippery surface was introduced one time without participants' knowledge and the data were collected to represent Slip1. A second slip trial was induced only when the subject

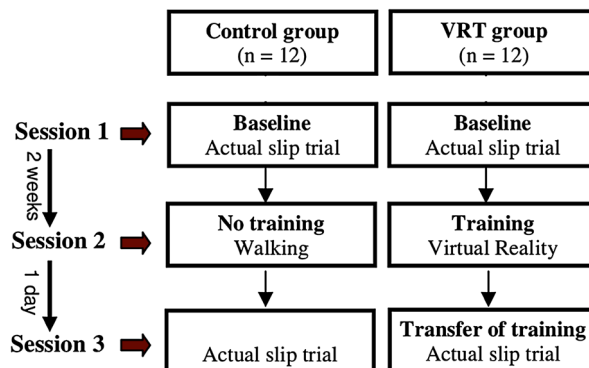


FIGURE 3. Experimental protocol for control and training group.

completely missed the slippery surface. Both groups underwent the Slip1 session.

Session 2 (Training Acquisition)

The control group underwent normal walking trials during their second session. Participants were instructed to walk on the track for 10–15 min. Data was collected from three normal walking trials during the experiment (Fig. 4).

The training group underwent virtual reality training in their second session. Participants were instructed to fill out the simulator sickness questionnaire (SSQ)⁸ to get their baseline cyber sickness scores. Following this, participants walked on the treadmill at a self-selected pace for 5 min wearing the harness. The initial baseline gait data on the treadmill was collected to represent treadmill walking without VR (TW). They were then instructed to wear the HMD with the virtual scene displayed. The HMD was adjusted so that the participants were looking straight ahead. After the participants felt comfortable with the HMD fit, the visual scene started moving and the treadmill speed was matched to the visual scene (keeping both at the comfortable pace for participants). Participants were instructed to walk for 15 min wearing the HMD and were told to rotate their head freely to feel the virtual environment, allowing for habituation of the virtual reality scene. During this habituation, 1 min kinematic data were collected at 5, 10, and 15 min to represent walking on the treadmill with VR (VR1, VR2, and VR3) (Fig. 5). After the habituation, participants were told to look straight ahead and that a slip may or may not be induced. They were instructed that if a slip is induced, they should try to recover balance and keep walking. A sudden virtual slip was induced by tilting the VR environment from 0° to 25° in the pitch plane at 60°/s. The virtual slip was randomly induced by pressing a key on the computer approximately at the heel contact of the right foot. The virtual slips were approximately 10–20 s apart. This tilting velocity and the tilting magnitude of the VR scene were chosen based on a pilot study conducted earlier to evaluate the speed and tilt at which perturbation was induced in older adults.

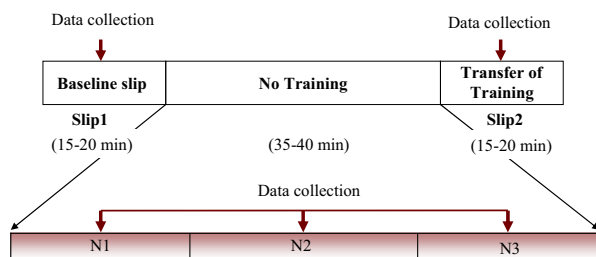


FIGURE 4. Experimental protocol for the control group.

Due to limited literature on use of VR as a perturbation training method, a previously used repeated perturbation training (i.e., moveable platform) paradigm was adapted for designing the training.¹ The training session consisted of 24 trials, with two blocks of slips and no slips, followed by random variations of slips and no slips (Fig. 5). After the first block of repeated slips, the speed of the virtual scene tilt was increased or decreased by 12°/s (20% of the initial velocity) for the next block of slip trials based on whether the participants successfully recovered from the perturbation (by observation). Unsuccessful recovery was determined when the participant's body dropped toward the floor after slipping and was arrested by the harness before impact.¹³ The decrease in velocity was believed to provide a better opportunity for successful recovery if failed recoveries were observed, whereas an increase in speed was believed to provide greater challenge if successful recoveries were observed; both of which has shown to improve motor learning.^{10,14} The last 12 trials included two slip velocities (from block 1 and 2) and no slip trials presented in a random order. The entire training session involved approximately 150 virtual slips.

Whole body kinematics and SSQ data were recorded during all trials to represent T1-T12 (Fig. 5). Data were also collected after end of block 1 and 2 to represent normal walking with VR on the treadmill (VR4 and VR5) (Fig. 5). Additionally, data were collected at the end of the training without the HMD to represent treadmill walking without VR (TW2) to test for any effect of VR on normal walking on the treadmill. The VR1–VR5 data were used to assess the changes in the gait variability with time in the VR.

Session 3 (Transfer of Training)

Both VRT and control group were brought back to the lab on the following day of the second session to test for transfer of training. The transfer of training

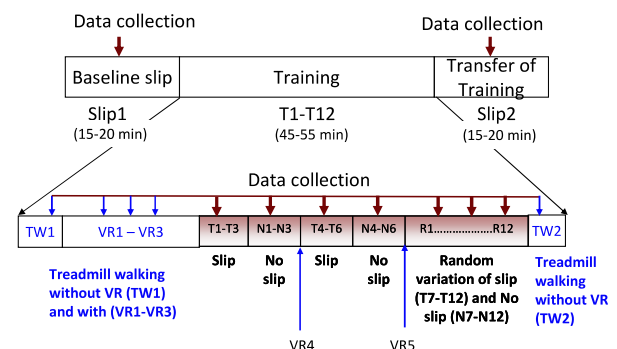


FIGURE 5. Experimental protocol for the virtual reality training group.

was tested on an actual slippery surface similar to the baseline measure. Participants were instructed to walk on the walkway at a self-selected pace which was matched with their pace during the first session using a metronome. The baseline kinematic and kinetic data were recorded before inducing the slip, representing the normal walking trials. After collecting the normal walking trials, a slippery floor surface was introduced without participants' knowledge and the data were collected (Slip2).

Data Analyses

The converted co-ordinate marker data and force plate data were low-pass filtered using a fourth order, zero lag, Butterworth filter at a cut off frequency of 7 Hz.¹³ Heel contact (HC) and Toe-off (TO) were identified from the ground reaction forces for Slip1 and Slip2 trials. For the training trials on the treadmill, heel marker data was used to identify HC and TO. All analyses were performed in the stance phase (HC to TO) of the slipping foot.

Gait Changes in VR Environment

To quantify gait changes while walking on the treadmill with VR, gait variability was assessed from the data that were collected at different time intervals (5, 10, 15, 20, 25 min). Parameters (see Table 2) that reflect gait instability such as changes in stride length, step width, variability in stride velocity, and variability in step width were calculated using the marker data.^{15,17} Variability in all of the above parameters was calculated as percentage coefficient of variation (% CoV). For variability calculations, 60 strides (~1 min walking on the treadmill) were chosen and then the mean and SD was calculated across all participants.

Reactive Responses After Slip Onset

Slip distances (SDI and SDII, see Table 2) indicative of severity of slips were calculated using the distance travelled by the slipping heel from slip-start to slip-end¹³ using the heel marker data. The peak sliding heel velocity (PSHV) along with the slip distances is used to predict the severity of a slip leading to a fall. The PSHV is defined as the peak heel velocity after the slip is initiated.¹³ As in our previous study,¹³ a slip trial was considered a fall if the slip distance exceeded 10 cm, peak sliding heel velocity exceeded the whole body COM velocity while slipping, and the participant's body dropped toward the floor after slipping and be arrested by the harness before impact.

Proactive Responses Before Slip Onset

Required coefficient of friction (RCOF) was defined as minimum ratio of horizontal to vertical ground reaction force.¹⁹

Statistical Analyses

The experiment employed a two-group pretest–posttest design. There were two independent variables: group (training vs. control), and training (Pre vs. Post). To determine the effect of virtual reality training on recovery performance, difference values were calculated between the two slips (Slip2–Slip1), and a one-way multivariate analysis of variance (MANOVA) was conducted between the two groups including all the dependent measures. The frequency of falls during Slip1 was analyzed between the two groups using the Chi square (χ^2) test statistic. Similarly, a Chi square test statistic (χ^2) was employed to analyze differences in the frequency of falls before and after the training session within group. A repeated measure ANOVA

TABLE 2. Summary of gait parameters.

Category	Parameters	Description
Gait changes in VR environment	Stride length	Anterior-posterior distance traveled (heel marker data) between consecutive heel contacts of the dominant foot
	Stride duration	Duration between consecutive heel contacts of the dominant foot
	Stride velocity	Ratio of stride length and stride duration
	Stride width	Mediolateral distance traveled (heel marker data) between consecutive heel contacts
Reactive changes	Slip distance I	Anterior-posterior distance traveled (heel marker data) from slip-start to mid-slip
	Slip distance II	Anterior-posterior distance traveled (heel marker data) from mid-slip to slip-end
Proactive changes	Peak sliding heel velocity	Peak heel velocity after the slip is initiated
	RCOF	Minimum ratio of horizontal to vertical ground reaction force on walking track

was conducted followed by post hoc test using Tukey's HSD to compare gait variability on the treadmill with and without VR during the training session. To determine if both groups had similar gait and slipping characteristics during Slip1, a one-way ANOVA was conducted on RCOF, SDI, SDII and PSHV. All statistical analyses were conducted using SPSS 11.5.0 (Chicago, IL) with a significance level of $p < 0.05$ for all tests. All of the data were explicitly evaluated for normality (using Shapiro–Wilk W test), and sphericity (using Bartlett's sphericity test). The results indicated no significant violation of the assumptions.

RESULTS

Gait Changes in Virtual Reality Environment

Significant differences were found in the stride length between treadmill walking with and without VR [$F_{(6, 76)} = 16.56, p = 0.001$]. Stride length decreased significantly in the VR environment (VR1–VR3). Compared to the stride length during TW1, the stride length decreased 11.9, 8.9, and 7.9% during VR1, VR1, and VR3, respectively. On the contrary, an increase of 2.0% in stride length was observed during VR4 than during TW1. *Post hoc* indicated no difference in the step length between VR5 and TW1 trials. Overall, the result indicates gait adaptation by being in the VR environment for 15–20 min. Similarly, significant differences were seen in the stride duration [$F_{(6, 76)} = 10.56, p = 0.002$] and step width [$F_{(6, 76)} = 9.56, p = 0.02$]. Stride duration increased initially in the VR environment (Fig. 6), and then decreased after walking in the VR for 15 min. However, step width increased by 2.5 cm at VR1, by 3.5 cm at VR3, and by 3.0 cm at VR5. *Post hoc* indicated a significant difference in the step width between TW1 and VR5 trial.

Variability in stride length was significantly different between treadmill walking with and without VR [$F_{(6, 76)} = 12.56, p = 0.001$]. Variability in step length

increased by 65% during VR1 trials and then reduced from VR2 to VR5 trials (Table 3), indicating no differences in the step length variability after walking in the VR for 25 min as compared to walking on the treadmill without VR. Similar results were found for variability in stride duration [$F_{(6, 76)} = 16.56, p = 0.0001$] and stride velocity [$F_{(6, 76)} = 10.56, p = 0.002$]. Variability in stride velocity increased by 84% after walking in the VR for 5 min (VR1), and was similar to TW1 by the end of VR5, indicating stable gait (Table 3). Variability in step width increased by 21% after walking in the VR for 5 min (Table 3), and then reduced from VR2 to VR5 trials. *Post hoc* results indicated a significant difference in the step width variability between VR5 and TW1 trials, indicating an increased variability during VR. Similarly, variability in stride duration increased by 58% at VR1, and then reduced from VR2 to VR5, being at the same level as TW1 at VR5.

Reactive Changes After Slip Onset

The VRT group was able to reduce the frequency of falls from 50% upon the first unexpected slip (Slip1) during the baseline trial to 0% upon the second unexpected slip (Slip2) during the transfer of training trial ($\chi^2 = 4.26, df = 1, p = 0.03$). Although the frequency of falls in control group reduced from 50% upon the first unexpected slip (Slip1) to 25% upon the second unexpected slip (Slip2), the difference was not statistically significant ($\chi^2 = 1.67, df = 1, p = 0.216$). Both VRT and control group were at a similar fall rate during Slip1 ($\chi^2 = 0.77, df = 1, p = 0.512$), accounting for no group differences at baseline. The MANOVA on the dependent variables during Slip1 and Slip2 indicated a significant effect of training [Wilk's lambda: $F_{(1, 18)} = 3.21, p = 0.03$]. Subsequent univariate analyses are as follows.

The ANOVA indicated that SDI and SDII decreased more from Slip1 to Slip2 in the VRT group

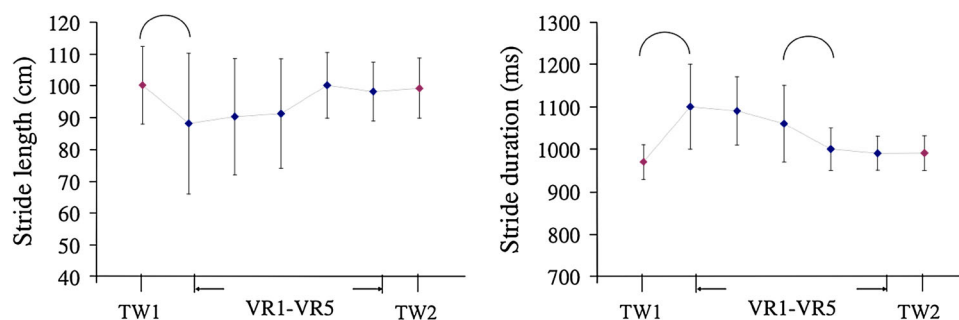
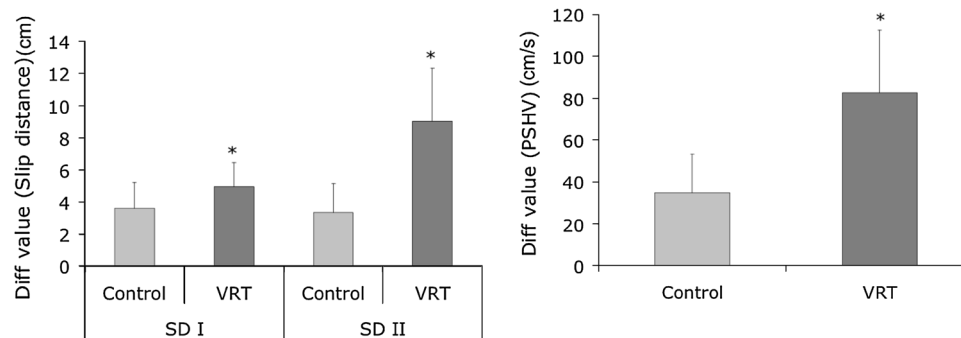


FIGURE 6. Mean \pm 1 SD of stride length and stride duration during normal treadmill walking trials (TW1), walking with virtual reality (VR1—5 min, VR2—10 min, VR3—15 min, VR4—20 min, VR5—25 min), and treadmill walking after training (TW2). ($n = 12$ participants, average of 1 min walking trials (~60 strides)). Connections indicate significant difference ($p < 0.05$).

TABLE 3. Mean \pm SD values for variability in stride length, stride duration, stride velocity, step width in virtual reality (VR), and no virtual reality (TW) environment.

Condition	Variability (%CoV)			
	Stride length	Stride duration	Stride velocity	Step width
TW1—No VR	12.20 \pm 2.23	4.78 \pm 1.23	5.23 \pm 1.78	33.78 \pm 10.23
VR1—5 min	20.17 \pm 9.34	9.12 \pm 3.25	9.63 \pm 3.55	42.76 \pm 12.34
VR2—10 min	18.88 \pm 7.56	8.67 \pm 3.19	7.19 \pm 2.88	41.67 \pm 10.33
VR3—15 min	17.17 \pm 6.34	6.08 \pm 2.66	7.98 \pm 1.98	39.33 \pm 10.23
VR4—20 min	10.31 \pm 5.34	5.21 \pm 1.88	6.22 \pm 1.23	38.23 \pm 11.48
VR5—25 min	10.39 \pm 3.45	4.23 \pm 2.12	5.92 \pm 1.91	37.66 \pm 10.45

**FIGURE 7.** Difference values (Slip2–Slip1) of slip distances (SDI, SDII) and peak sliding heel velocity between control and training group (* $p < 0.05$, ** $p < 0.01$).

compared to control [SDI: $F_{(1, 18)} = 10.34$, $p = 0.01$; SDII: $F_{(1, 18)} = 5.27$, $p = 0.03$] (Fig. 7), suggesting improved reactive changes after slip. Specifically, after training, the SDI was reduced 47.7% in the VRT group and only 24.1% in the control group. Similarly, after training, the SDII was reduced 50.8% in the VRT group and only 16.2% in the control group. Greater decrease in the peak sliding heel velocity was also observed for the VRT group (Table 4) compared to control [$F_{(1, 18)} = 4.54$, $p = 0.05$]. Specifically, the VRT group reduced the peak sliding heel velocity by 39.0%, while the control group reduced by 18.5%. It should be noted that no significant differences were found between the groups in the slip distances and peak sliding heel velocity during Slip1, suggesting no group differences at the baseline.

Proactive Changes at Heel Contact Before Slip Onset

The results indicated few proactive adjustments in the VRT group at heel contact during the transfer of training trial (Slip2). Both VRT and control group had no significant differences in the walking speed during the Slip1 and Slip2 trials. No significant differences were observed in the friction demand characteristics (RCOF) between Slip1 and Slip2 trials in both control and VRT group. No significant differences were observed in the ankle, knee, and hip kinematics at the heel contact before the slip onset between groups.

Proactive and Reactive Strategies During Virtual Reality Training

As hypothesized, the virtual reality training reduced the incidence of balance loss from training trial T1 to T12. During the first block of training trials (T1–T3), there was 75% (9/12) incidence of balance loss, which reduced to 0% from T4 to T12 trials. After the first 2–3 training trials, participants walked without any reactions to the subsequent virtual slips (T4–T12). Therefore, recovery parameters were observed only from T1 to T3. Once the virtual slip was induced, it took participants an average of ~200–300 ms to initiate recovery attempts, mainly by a quick stepping response of the non-slipping foot. The SSQ score (mean \pm SD) was found to be 0 before the VR training, 5.93 ± 2.46 immediately after training, and 0.66 ± 0.81 on the next day after training. This result indicated minimal presence of cyber sickness after being in the VR for 25 min (a score of 20 or more indicates cyber sickness).

DISCUSSION

This study examined the use of a novel virtual reality perturbation method in training motor skills specific to recovery from a slip-induced fall. The study findings support the use of VR as a perturbation-based training tool for older adults. Although, the visual tilts of the VR

TABLE 4. Mean \pm SD of slip parameters during Slip1 and Slip2 trials between control and training group.

	Group			
	Training		Control	
	Slip1	Slip2	Slip1	Slip2
Slip distance I (cm) ^a	10.37 \pm 3.97	5.42 \pm 3.56	12.34 \pm 6.34	9.36 \pm 4.25
Slip distance II (cm) ^a	17.77 \pm 4.01	8.74 \pm 3.98	20.63 \pm 6.25	17.29 \pm 4.67
Peak sliding heel velocity (cm/s) ^a	185.22 \pm 39.29	112.97 \pm 28.29	190.63 \pm 86.25	155.29 \pm 75.67

^a $p < 0.05$, p value represent the statistics on the difference value (Slip2–Slip1) between groups.

could not induce postural perturbation after the initial 2–3 trials, a potential application of VR in designing slip training program for older adults is identified. The VRT group was able to reduce incidence of balance loss when experienced with an actual slippery surface after the training compared to the controls.

Even though prior research has exhibited presence of gait variability while walking on a treadmill with VR,⁵ it was found that the time spent in the VR environment was directly proportional to the reduction in gait variability and instability. Older participants walked with an increased variability of stride length, and stride velocity during the initial 5–10 min in the VR, which is similar to the findings by Hollman *et al.*⁵ Contrary to previous findings,⁵ however, no clear pattern was present in step width variability in the current study. Such discrepancies are likely to be due to the age-related differences between studies. The initial instability may be because the HMD worn during the experiment completely masked the participants' peripheral vision and they did not have any visual contact with the treadmill belt. This may have caused participants to adopt a cautious gait. However, the variability in stride velocity and stride length reduced after walking in the VR for 15 min, approximating gait variability during treadmill walking without VR. After walking for 15 min in the VR environment, the kinematic responses approximated treadmill walking without VR. Additionally, the SSQ scores collected from the participants during the VR walking (25–30 min) and after the experiment indicated no presence of eyestrain, dizziness, nausea or fatigue. These results have potential applications in developing future VR setups for improving locomotion research. The habituation time should be considered as one of the important factors while designing a VR locomotion study so that the effects of optical flow on gait behavior are not masked.

The VR training had beneficial effects in improving recovery reactions in older adults when experienced with a slippery surface after the training. The visual tilts were introduced after the participants had walked for 15 min in the VR environment to ensure habituation. The pitch plane movement was able to induce

perturbations in the participants during the initial 2–3 trials, which invoked recovery reactions such as stepping of the non-slipping foot, increasing trunk flexion, and sometimes a fall. A ceiling effect was observed after the initial trials, where participants did not react to any visual perturbations. Due to the limited trials (2–3) per participant, it is difficult to generalize recovery reactions learned during the training. However, when participants came back for the transfer of training trial (Slip2), their fall incidence was lowered from 50% during Slip1 to 0% during Slip2. Although, fall frequency decreased in controls also during Slip2 (50–25%), there were two participants who experienced a fall both during Slip1 and Slip2, and one participant experienced a fall during Slip2 and not during Slip1. Such inconsistencies were not observed in the training group, where all participants those who experienced fall during Slip1 recovered during Slip2. Additionally, slip severity measures such as slip distances and peak sliding heel velocity decreased more for the training group. Reducing the distance traveled by the slipping foot reduces the likelihood of falling.^{2,19} Slips were initiated at similar time intervals for both the training and control group during Slip1 and Slip2 trials. However, time required for slip-stop was reduced in the training group compared to the control group during Slip2 trial, which may have reduced the severity of slips and led to a successful recovery.

One of the significant contributions of this study is the use of VR environments in inducing perturbations similar to a slip, which has only been suggested in the previous studies.^{9,16} Additionally, the study verified that healthy older adults were able to stabilize their gait in the VR environment after a habituation period, which is contradictory to previous studies that found increased variability in the gait after VR walking.⁵ The discrepancy may be attributed to the differences in the experimentation time in the VR environments in the earlier studies (3–5 min as compared to 25–30 min in this study). The habituation time in VR is important while designing future locomotion research using virtual environments.

Several limitations existed in the study. Participants adapted to the virtual slips within 2–3 trials, and subsequent perturbation could not be induced. Due to this

ceiling effect and a large variability in the data, few recovery strategies during training could be reported and the results could not be generalized. Additionally, because participants were walking on the treadmill while the virtual slip was induced, certain recovery strategies were masked, as there was an additional demand on the participants to keep moving on the treadmill. Future studies may explore using a manual treadmill, where participants can control their speed of walking. The current study only recruited healthy older adults and therefore it is unclear how different population samples such as fall prone individuals will adapt to a virtual reality environment. Relevant factors such as mobility history and gender should also be explored in the next step. In addition, the effect of transfer was evaluated 1 day after the VR training. Thus, the study results should not be generalized beyond the transient effectiveness of the training.

Future studies may explore different ways to induce visual tilts in the VR to make the perturbation novel to the participants each time. It is important to test if similar VR adaptations can be seen in a larger cohort of older adults. Furthermore, future work should consider having the control group also walk on the treadmill with regular VR scenes with the objective to better isolate the effect of VR slip training. In addition, future studies may explore the retention of the training effects after a period of months. A longitudinal study may be conducted to follow the current participants post training to report their fall frequency.

In summary, findings from this study indicate that the VR training was able to induce a perturbation in older adults that evoked recovery reactions. Older adults were able to adjust to the perturbation scenario and walked without any reactions after 2–3 trials. Participants were able to adjust their gait variability to that of treadmill walking after being in the VR for 15–20 min, indicating a stable gait. The training group had a better recovery performance as compared to the control group that led to a decrease in the incidence of falls. Improvements in the recovery performance were mainly attributed to the reactive strategies employed by the training group.

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CONFLICT OF INTEREST

The authors have no conflicts of interest related to this study.

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