Preventing Slip-induced Falls in Older Adults: Perturbation Training using a Moveable Platform and Virtual Reality

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(Abstract)

Slip-induced fall related injuries are a serious public health issue among older adults leading to considerable mortality, morbidity, and immobility. Existing proactive exercise interventions have produced mixed results on the success of reducing fall accidents. A training intervention may be effective in reducing slip-induced falls, if it can help older adults to practice movements related to recovery responses.

The purpose of this study was to evaluate two different training interventions using a moveable platform and virtual reality in order to improve reactive recovery in older adults. Thirty-six older adults were recruited and randomly assigned to three groups (moveable platform training, virtual reality training, and control). The training groups underwent three sessions including baseline slip, training, and transfer of training on a slippery surface. The control group underwent three similar sessions as the training groups, with the training session replaced with a normal walking session. Kinematic, kinetic, and EMG data were collected during all the sessions. The moveable platform training group was repeatedly exposed to simulated slips induced by anterior-posterior movement of a platform. The virtual reality training group was repeatedly exposed to perturbation induced by visual tilts in the virtual environment while walking on the treadmill. Various biomechanical and neuromuscular characteristics were identified to quantify the effects of training.

The results indicated a beneficial effect of both training methods in improving recovery reactions in older adults via proactive and reactive adjustments. The reactive adjustments involved faster response to a slip perturbation mediated by reduced time for onset and peak muscle activation (specifically knee flexor), reduced knee and ankle coactivity, reduced time for peak knee, hip, and trunk angles, and angular velocity. The proactive adjustments involved an increased center-of-mass velocity and transitional acceleration of center-of-mass. The overall fall frequency was reduced in the training groups as compared to the control group through improvements in proactive and reactive responses.

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CHAPTER 1 – OVERVIEW

RATIONALE

Fall accidents are a common and serious problem in older adults. Annually, one in three Americans over the age of 65 years experience a fall, and many of these falls are recurrent (Hausdorff et al., 2001). Among these, slip-induced falls account for 87% of all hip fractures, which often results in functional impairments and may require admission to a nursing home facility (Sterling et al., 2001). The total cost due to fall injuries was $27.3 billion in 1994 and is expected to increase to $43.8 billion by 2020 (Donald et al., 1999; Englander et al., 1996). Due to increases in life expectancy in the past century, the size of the older population (>65 years) is growing and is expected to reach 54.6 million by 2020 (U.S. Census Bureau, 2006). Because the prevalence of fall injuries is high among older adults, there is a need for prevention strategies that will help reduce the risks associated with falls.

Currently, there are two strategies for reducing fall injuries; fall protection and fall prevention, which are also known as reactive and proactive strategies respectively. Protection strategies refer to interventions aimed at reducing injury severity once the fall is initiated (i.e., hip protection pads, fall arresting harness, helmets). There are certain limitations associated with the existing fall protection strategies including user compliance (Kannus et al., 2000). Additionally, existing fall protection strategies cannot prevent an incident from occurring (Smith & Veazie, 1998). On the contrary, proactive strategies may be able to help prevent a fall. Fall prevention strategies refer to environmental control as well as interventions aimed at improving balance and stability in the elderly. In terms of environmental control, it is believed that maintaining a safe level of coefficient of friction (COF) of floor surfaces is important in preventing slip-induced falls (Gronqvist et al., 1989). However, there is no clear consensus on the safe floor COF and there is a lack of standard measurement method for floor COF (Courtney et al., 2001). These limitations hinder the use of COF as a control to prevent fall accidents.

An alternate fall prevention strategy is improving stability in the elderly through physical exercises. Numerous exercise interventions have been suggested to prevent falls in the elderly (i.e., strength, endurance, balance). These exercises when repeated on a daily and weekly basis have shown to improve postural control by generating adaptation of the neuromuscular system (Perrin et al., 1998; Hakkinen et al., 1996). However, several studies have produced mixed results on the success of these exercise programs in terms of reducing fall accidents (Mansfield et al., 2007; Kannus et al., 2005; Mclroy et al., 2002). This may be because most of the training programs are designed to improve some components of posture control (i.e., strength, proprioception) (Hakkinen, 1996), and the results may not be generalized to situations like recovering from a slip-induced fall. Generally, if there is a similarity in stimulus-response elements between training and performance, a positive transfer may occur. The most effective type, intensity and duration of training that can effectively reduce fall accidents is yet to be identified (Kannus et al., 2005).

In terms of slip-induced falls, the slip detection and recovery phase are the most critical to avoid or arrest a fall (Lockhart et al., 2005). The execution of a successful reactive recovery can be viewed as a form of dynamic feedback control with afferent sensory input from visual, vestibular and proprioceptive receptors (Lockhart et al., 2005; Fransson et al., 2003). The slip detection phase involves processing of the sensory inputs to the central nervous system and triggering the appropriate response selection (Lockhart et al., 2003). The reactive recovery phase involves bringing the whole body center-of-mass (COM) over the base of support quickly after a slip is initiated. This is achieved through changes in various kinematic, kinetic, and muscle coactivity mechanisms. One of the important mechanisms during reactive recovery is to reduce the displacement of the slipping foot by stabilizing the joints through coactivity of the muscles of the lower extremity (Lockhart & Kim, 2006; Brady et al., 2000). Additionally, increased knee flexion, hip extension and trunk flexion is required to recover from a slip (Lockhart & Liu, 2006; Ferber et al., 2000). The unperturbed limb plays an important role in recovering from a slip by increasing the base of support through rapid stepping (Oddson et al., 2004). Furthermore, the force generating capacity of the lower extremities may play an important role in the recovery process (Lockhart & Liu, 2006). Numerous studies have reported age-related degradation in integration and co-ordination of motor and sensory abilities (Seidler et al., 1995; Stelmach &

Sirica 1986; Skinner et al., 1984). A decline in these abilities may compromise older adults' selection of recovery responses required for balance and thus predispose them to a higher risk of falls.

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. (2006) demonstrated improved recovery in young adults after repeated exposure to a simulated slip-perturbation. Similarly, Pai et al. (2003) 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. These findings suggest a potential application of repeated perturbation training as a slip recovery intervention for the elderly.

Slip perturbation training can be performed in various ways, one of which is to repeatedly perturb individuals using a motorized platform. The idea is to produce an overall sensory conflict (similar to a slip) by perturbing the somatosensory system via moving the platform/floor surface underneath the foot while walking. If the speed/acceleration of the motorized platform is matched to characterize an actual slip, participants may elicit similar muscle activations and stepping responses to recover from the perturbation. Although implied, no studies to date have investigated the effects of repeated slip training on an actual slippery surface, and the potential of this medium to enhance transfer of training. Additionally, the effectiveness of perturbation training in reducing fall accidents in older adults, and, several pertinent factors such as intensity and duration of training needs to be investigated.

An alternate perturbation training that may simulate the visual-vestibular conflict experienced when balance is challenged is through the use of an immersive virtual reality environment. Recently, Nyberg et al. (2006) demonstrated changes in walking speed, stride length, balance reactions and slips among individuals who were exposed to an immersive VR environment (i.e., visual tilt, heavy snowfall). Similarly, Bugnariu et al. (2007) observed that when a virtual environment was manipulated to provide a distorted visual perception, older adults took more steps to maintain upright stance and had delayed onset of muscle activity. This may be due to the impairments of sensory organization in older adults, especially the visual modality during balance maintenance (Bugnariu et al., 2007; Lockhart et al., 2005; Holden et al., 1999). In addition, a general training effect (i.e., less stepping response, improved ability to maintain balance) was observed in older adults through repeated exposures to the VR-induced sensory conflicts (Bugnariu et al., 2007). Although these studies induced VR distortions during quiet standing, automatic postural responses were seen in both young and old adults. Based on these findings, it is reasonable to assume that a VR environment could induce repeated virtual slips via visual-vestibular conflict, causing individuals to elicit reactive recovery responses (i.e., increased muscle coactivity, head and neck motion, and trunk flexion) similar to an actual slip. Although studies have suggested that training with VR may induce goal-directed practice and thus be used in fall prevention programs (Hollman et al., 2007; Nyberg et al., 2006; Keshner et al., 2004), no current VR training is available that aims to improve recovery reactions in older adults. Additionally, the notion of whether learned responses associated with VR training can be translated to an actual slip needs to be investigated.

In summary, slip-induced falls are a leading cause of fatal and non-fatal injuries in older adults. Aging is known to cause a decline in the sensorimotor integration and muscular co-ordination. Several exercise programs have been suggested to improve balance in the elderly, but the retention of these abilities and the success in preventing falls after training is not well documented. A training intervention may be effective in reducing slip-induced falls, if it can help older adults to practice movements related to recovery. This type of training may improve their overall sensory integration and muscle co-ordination and, the ability to recover from an actual slip perturbation. Recently, it has been found that repeated exposure to slip perturbation have reduced the incidence of balance loss in young adults due to adaptations of the central nervous system. However, efficacy of such training programs for older adults and transfer of this training on a slippery surface needs to be further investigated.

SPECIFIC AIMS

The aim of this study was to evaluate two different kinds of perturbation training methods that could improve recovery responses in older adults. The study evaluated the efficacy of moveable platform training (MPT) and virtual reality training (VRT) in reducing fall accidents. All groups (control, MPT, and VRT) were exposed to a slippery surface before and after the training to quantify transfer of training.

Specific Aim 1: To evaluate the biomechanical and neuromuscular changes by which moveable platform training improves proactive and reactive responses in older adults and demonstrate its feasibility in reducing fall frequency.

Hypothesis 1a: The training group will have reduced slip severity as measured by slip distances (SDI and SDII), peak sliding heel velocity, and reduced fall frequency when exposed to an actual slippery surface after training as compared to the control group.

Hypothesis 1b: The training will influence recovery kinematics (knee flexion, hip extension, and trunk flexion) and muscle coactivations (peak coactivation index, activation onset) in the training group when recovering from a slippery surface as compared to the control group.

Hypothesis 1c: The training group will have proactive adjustments (increased COM velocity, increased transitional acceleration of COM) during heel contact phase when exposed to a slippery surface as compared to the control group.

Specific Aim 2: To design a virtual reality based training to induce perturbation in older adults and evaluate the biomechanical and neuromuscular changes by which the training improves proactive and reactive responses in older adults, and demonstrate its feasibility in reducing fall frequency.

Hypothesis 1a: The training group will have reduced slip severity as measured by slip distances (SDI and SDII), peak sliding heel velocity, and reduced fall frequency when exposed to an actual slippery surface after training as compared to the control group.

Hypothesis 1b: The training will influence recovery kinematics (knee flexion, hip extension, and trunk flexion) and muscle coactivations (peak coactivation index, activation onset) in the training group when recovering from a slippery surface as compared to the control group.
Hypothesis 1c: The training group will have proactive adjustments (increased center-of-mass velocity, lower extremity angular kinematics) during heel contact phase when exposed to a slippery surface as compared to the control group.

Specific Aim 3: To compare the efficacy of moveable platform training and virtual reality training in improving recovery responses in older adults when exposed to a slippery surface, and reducing fall frequency.

Hypothesis 3a: The moveable platform group and virtual reality group will have reduced slip severity and reduced fall frequency when exposed to a slippery surface.
Hypothesis 3b: The reactive strategies employed (angular kinematics, muscle activations, coactivations) by the moveable platform and virtual reality training group will differ during the transfer of training trial.
Hypothesis 3c: The proactive adjustments at heel contact employed (increased center-of-mass velocity, lower extremity angular kinematics) by the moveable platform and virtual reality training group will differ during the transfer of training trial.

Document Organization

This dissertation is organized into five chapters. Chapter 2 presents the moveable platform training and explores the first specific aim. Chapter 3 presents the virtual reality training and explores the second specific aim. Chapter 4 compares the two training interventions in reducing fall frequency in older adults. Finally, Chapter 5 highlights the major findings, future directions and conclusions.

CHAPTER 2 – EFFECTS OF MOVEABLE PLATFORM TRAINING IN PREVENTING SLIP-INDUCED FALLS IN OLDER ADULTS

ABSTRACT

Identifying effective interventions is key to prevent slip-induced fall accidents in older adults. The purpose of the current study was to evaluate the efficacy of moveable platform training in improving recovery reactions and reducing fall frequency in older adults. Twenty-four older adults were recruited and randomly assigned to two groups (training and control). Both groups underwent three sessions including baseline slip, training, and transfer of training on a slippery surface. Both groups experienced two slips, one during the baseline and the other during the transfer of training trial. In the training session, the training group underwent twelve simulated slips using a moveable platform while the control group performed normal walking trials. Kinematic, kinetic, and EMG data were collected during all the sessions. Results indicated 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 proactive and reactive control strategies learned during training to the second slip trial. The proactive adjustments include increased center-of-mass velocity and transitional acceleration after training. Reactive adjustments include reduction in muscle onset and time to peak activations of knee flexors and ankle plantarflexors, reduced ankle and knee coactivations, reduced slip displacement, and reduced time to peak knee flexion, trunk flexion, and hip flexion velocities. In general, the results indicated a beneficial effect of training in reducing slip severity and recovery kinematics in healthy older adults.

INTRODUCTION

Fall accidents are associated with considerable medical cost and suffering in older adults. Annually, 33% of older adults (> 65 years) experience a fall and many of these falls are recurrent (Hausdorff et al., 2001). Slip-induced falls account for 87% of all hip fractures, which often results in immobility and may require admission of the older adults to a nursing home facility (Sterling et al., 2001). As the size of the older population (> 65 years) is growing and fall injuries remain prevalent in this age group, there is a need for prevention strategies to reduce the risks associated with falls. Numerous exercise interventions based on strength training (Buchner et al., 1997), balance training (Steadman et al., 2003), and Tai Chi (Woo et al., 2007) have been proposed to prevent falls. However, efficacy of these interventions in reducing fall rates have produced mixed results (Mansfield et al., 2007; Kannus et al., 2005; Campbell et al., 1997). The differences may be because most of the training programs are general in nature and not designed to improve specific motor skills related to recovering from a slip-induced fall.

A training program that may help 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 postural perturbation (i.e., slip). Perturbation-based training using an anterior-posterior motion of a moveable platform has shown to evoke recovery reactions similar to slip-induced fall. The perturbation training in general follows the principle that the central nervous system will continuously adapt and adjust to postural disturbances induced to maintain balance. Numerous studies have used repeated perturbations to observe improvements in adaptive responses (Lam et al., 2006; Tjernstrom et al., 2002; Weber et al., 1998; Gordon et al., 1995). Lam et al. (2006) examined the strategies used by participants to adapt their walking pattern to a velocity-dependent resistance applied against their knee and hip movements. The results indicated immediate increases in hip and knee muscle activity during swing phase in the presence of resistance. These adaptive changes were believed to be caused by the involvement of feedforward and feedback control. Similarly, there is evidence for long-lasting modifications in the inter-limb co-ordination after a period of walking on a rotating disk (Weber et al., 1998; Gordon et al., 1995) or a split-belt treadmill (Jensen et al., 1998). The presence of aftereffects following a period of training under new conditions implies the process of "re-learning" the motor output for a given task.

Recently, Bhatt et al. (2006) demonstrated improved recovery in young adults after repeated exposures to a simulated slip-perturbation. Slips were induced using a moveable platform (free to slide when unlocked) that shifted unexpectedly when the participants walked over it. This created an overall sensory conflict (similar to a slip) by perturbing the somatosensory system. Improvements were seen both during pre-slip and post-slip COM stability, with participants reaching a steady state after a few trials. These adjustments to repeated perturbations reflect an individual's adaptability in stability control within the CNS. Similarly, Bieryla et al. (2006) demonstrated improvements in trip recovery following repeated trip perturbations on a treadmill in older adults. Pavol and Pai (2002) found a decreased incidence of falls in older adults with repeated slip exposure during a sit to stand task. These studies provide evidence that older adults have the capability to adapt their movements to recover from a perturbation through training.

Although the previous studies examined the adaptation of individuals to the simulated slip-perturbation training, none of the studies assessed the effects of the training on an actual slippery surface. Additionally, there is a need to assess the extent to which such training effects can be reproduced in older adults. Further, little is known about the various biomechanical and neuromuscular mechanisms that may be utilized by older adults to recover when exposed to such perturbation training.

The objective of the current study was to evaluate the effects of moveable platform training at improving recovery in older adults and reducing fall frequency. Additionally, the purpose of the study was to identify the various biomechanical and neuromuscular changes that occur during the moveable platform training (MPT). It was hypothesized that the MPT group would be able to transfer strategies learned during the training to an actual slip.

METHOD

Participants

Twenty-four healthy older adults (> 65 years, 12 males, and 12 females) were recruited for the study from the local community (Table 2.1). The sample size was estimated using power analysis on preliminary test results. A written consent form, approved by the Institutional Review Board (IRB) of Virginia Tech, was obtained from the participants before participation. Exclusionary criteria included cardiovascular, respiratory, neurological, and musculoskeletal abnormalities as well as any other difficulties hindering normal gait (Appendix A). In addition, a physician screened participants for lower extremity (ankle, knee, hip, heel and toe) range of motion, and any balance related problems (Rhomberg, light touch test). Participants were randomly divided into a control group (n = 12), and a moveable platform training group (n = 12). No significant differences were found in the demographics of participants between groups (Table 2.1).

Table 2.1 Participants demographics (Mean ± SD)

	Group		
	Control (n = 12)	Training (n =12)	P value
Age (yrs)	74.18 ± 5.82	71.24 ± 6.82	0.91
Mass (kg)	69.63 ± 9.45	68.24 ± 8.04	0.78
Stature(cm)	169.41 ± 9.16	167.45 ± 11.52	0.11

Note. The P value represents the results of a t test comparing two-groups

Apparatus

Moveable platform set-up

The slip perturbation training was conducted by inducing slips using a custom built sliding device consisting of a low friction, motorized moveable platform (40x120cm) (motor: DSM030, Electro-Craft, MN). The moveable platform was embedded into an existing 15 m walkway and was covered with the same vinyl floor material as that of the walkway (Fig 2.1). One force plate (BP400600-1000, AMTI, MA) was placed next to the moveable platform so that the ground reaction force of the step prior to contacting the platform could be recorded. Slips were induced by a computer-controlled program that moved the platform right after the heel contact of the slipping foot, when the vertical ground reaction force of the trailing limb dropped below a threshold (i.e., 40% of body weight was lifted off the force plate) (Fig 2.2). This platform movement simulated a backward fall when slipping over a slippery surface (anterior motion of the platform as compared to the body). The computer program, written in LabVIEW 6.2 (National Instruments, Austin, TX), was used for the real-time monitoring of the force and required individual's weight (in kg) as an input parameter (Fig 2.2).

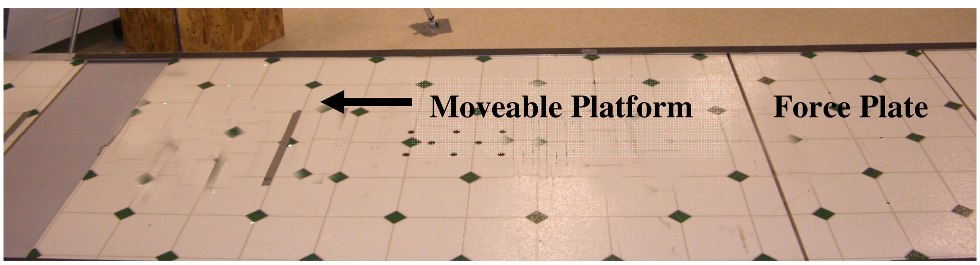

Figure 2.1 Experimental lay-out of moveable platform training set-up with the motorized platform and force plate.

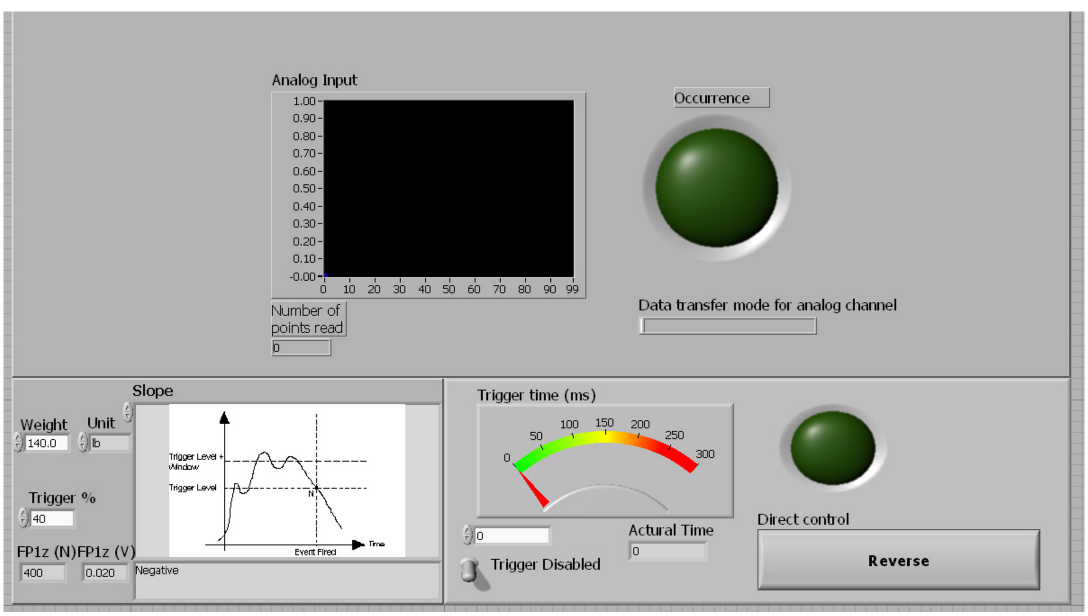

Figure 2.2 LabVIEW program interface for triggering the moveable platform.

Actual slip-perturbation set-up

Both groups performed slip trials on a slippery floor surface twice (before and after the training/normal walking). The second slip trial served as the transfer of training trial for the training group. The slip trials were conducted on a 15 m long walkway. The walkway was embedded with two force plates (Type 45550-08, Bertec Corporation, USA) which were used to record gait characteristics and induce an actual slip (Figure 2.3). The position of the two force plates was different from that of the moveable platform set-up. The slippery surface (i.e., top of one the force plates) was covered with a water and jelly mixture (1:1) to reduce the coefficient of friction (COF) (dynamic COF = 0.12) of the floor surface. The dynamic coefficient of friction was tested for the 1:1 water and jelly mixture using the standardized procedure (Lockhart et al., 2002). The participants were unaware of the position of this surface as the force plates are covered with the same vinyl as the walkway. This is a standardized approach used in several previous slip and fall studies (Lockhart & Liu, 2006; Lockhart et al., 2005). The experimental layout is shown in Figure 2.3.

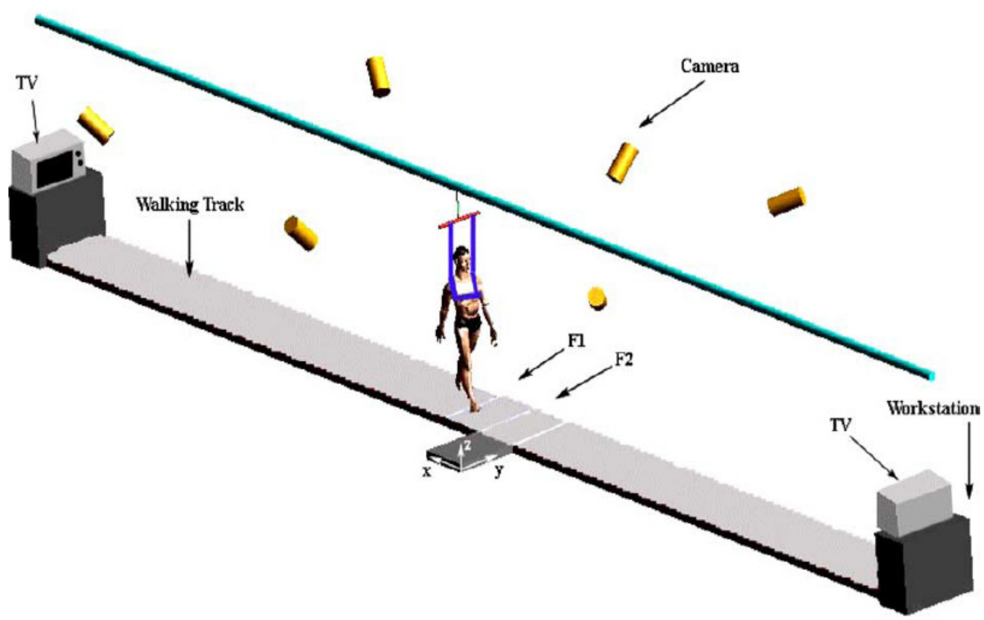

Figure 2.3 Experimental set-up for the baseline and transfer of training session including the walkway, two force plates (F1 and F2), and a six camera motion capture system.

Measurement

Full-body kinematics were recorded at 100 Hz using a six-camera motion capture system (Qualisys). 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)), and one marker at the center of the moveable platform. The marker configuration is similar to previous studies (Lockhart et al., 2003). Kinetic data were collected at 1000 Hz from the force plates. An eight-channel EMG telemetry Myosystem 2000 (Noraxon, USA) was used to record temporal activations of various muscles in the lower extremity during all the sessions. The force plates and EMG system were connected to a 16 bit, 64 analog-input, DAQ card (PCI-6031E, 100kS/s, NI, USA). Bipolar surface electrodes (Ambu Blue sensor P, AMBU, Denmark) were placed bilaterally over vastus lateralis (VL), medial hamstring (MH), tibialis anterior (TA) and medial gastrocnemius (MG) muscles. The EMG data were sampled at 1000Hz. A LabVIEW program synchronized the data collection from the motion capture system, force plates, and EMG system. Uniform clothes and shoes were provided to all participants to minimize loose clothing and shoe-sole differences. Participants wore a full body fall-arresting harness throughout the experiment (Lockhart et al., 2003).

Protocol

The experiments were divided into three sessions: baseline measure, training acquisition and transfer of training, on three separate days (Fig 2.4). During the first session, all participants underwent a slip trial on a slippery floor surface as a baseline measure. After two weeks, the training group performed the slip training and the control group performed normal walking trials. The third session was on the following day of the training, where both groups were exposed to a slippery floor surface similar to the baseline session.

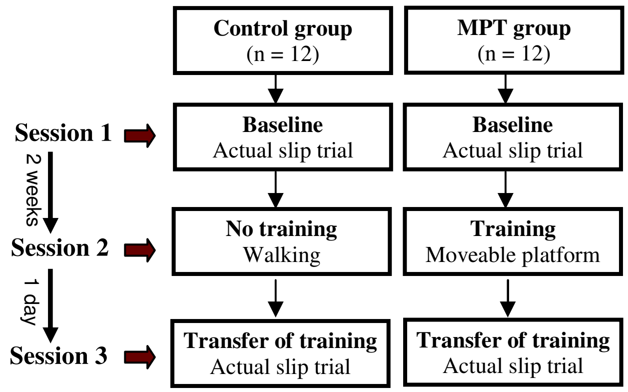

Figure 2.4 Experimental protocol for control and training groups

Baseline Measure

Participants were instructed to walk on the walkway for 10 minutes at a self-selected pace to become familiarized with the harness and the lab environment. A metronome was used to record participants' self-selected pace (used in subsequent sessions). The starting point of their walking was adjusted so that their right foot landed on the force plate at the center of the walkway, which was later switched to a slippery surface (Figure 2.3). The baseline kinematic, kinetic, and EMG data were recorded from five walking trials before inducing the slip. The participants were told that they "may or may not slip" and that if they did, they should try to recover their balance and keep walking. After collecting the normal walking trial, an actual slippery surface was introduced without the participants' knowledge and the data were collected (Slip1). Based on the group assignment, participants were called for their next session (moveable platform training or control walking session) (Fig 2.4).

Training Acquisition

The control group underwent normal walking trials during their second session. After attaching the markers and EMG sensors, participants were instructed to walk on the walkway for 15-20 min at their self-selected pace. Simple filing tasks were provided to the participants at the end of the walkway (Fig 2.3). The training group underwent moveable platform training in their second session. Participants were attached with the electrodes and sensors and were instructed to walk on the walkway at their self-selected pace. The walking speed was monitored using a metronome, and was matched to their pace recorded from the first session. Participants' initial gait data (5 walking trials) were recorded using the motion capture, force-plate, and EMG system. In addition, the starting point of their walking was adjusted such that their non-slipping foot (left) landed on the force plate located prior to the moveable platform. Participants were told that they "may or may not slip", and that in case they slip, they should try to recover their balance and keep walking. Participants were unaware of the position of the moveable platform and the time of perturbation. After collecting data from the walking trials, a simulated slip was induced by moving the platform 0.3 m at a speed of 1.2 m/s (acceleration at 20 m/s^2). The distance and velocity chosen for the training was based on a pilot study conducted earlier to evaluate the parameters at which older adults elicited recovery reactions. Additionally, these values are comparable to slip distances and peak sliding heel velocity during actual slips (Brady et al., 2000). After the first exposure to the simulated slip, the participants were instructed to continue walking at the same speed as that of the previous trial and that they may or may not be slipped again.

The training session consisted of 24 trials, consisting of a block of three repeated slips (T1-T3), then a block of three no slips (N1-N3), followed by a second block of three repeated slips (T4-T6), another block of three no slips (N4-N6), followed by 12 trials of random variations of slips and no slips (R1-R12) (Fig 2.5). A combination of blocked and randomized practice sessions have been shown to enhance motor leaning (Lee et al., 1991). The structure of the training session is similar to the protocol adopted by Bhatt et al. (2006). However, after the first block of repeated slips, the speed of the moveable platform was increased or decreased by 0.24 m/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). The decrease in velocity was believed to provide a better opportunity for successful recovery in cases where failed recoveries were observed, whereas an increase in speed was believed to provide greater challenge, if successful recoveries are observed; both of which has been shown to improve motor learning (Mansfield et al., 2007; Kottke et al., 1978). The last 12 trials included two slip speeds from block 1 and 2 trials, and no slip presented in a random order. Whole body kinematics, kinetic, and EMG data were recorded during all the trials.

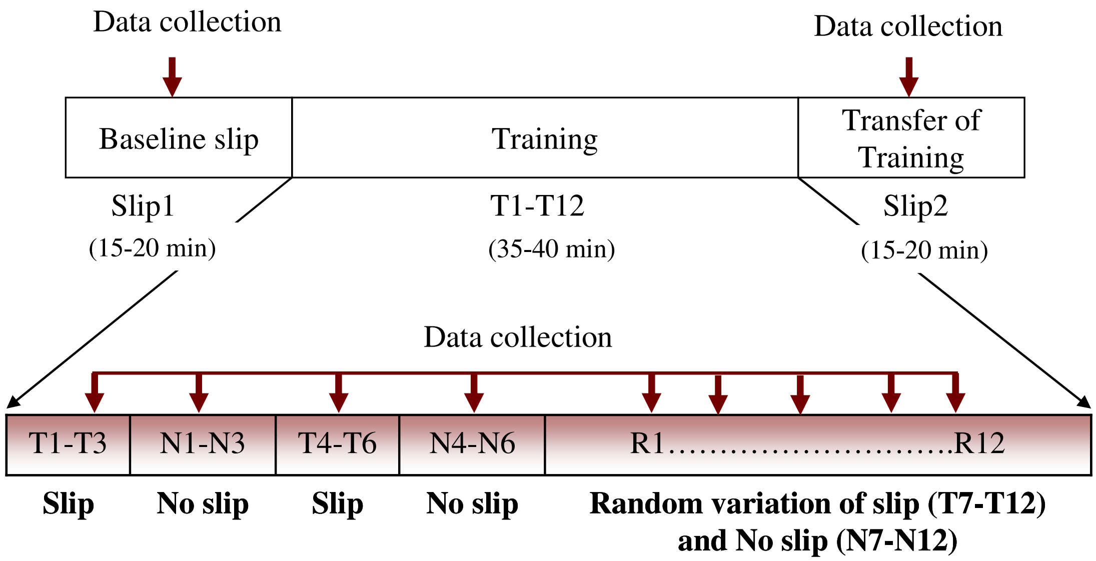

Figure 2.5 Experimental protocol for moveable platform training consisting of 24 trials of blocked slip and no slip trials (12), and randomized slip and no slip trials (12).

This training adheres to the principles of *progressive overload*, as progressions were made by increasing the magnitude of perturbation whenever the subject was able to recover, thus increasing challenge to the motor control system (Drowatzky et al., 1999). Progressions were matched to the individual's rate of adaptation; thus, the magnitude of the perturbation induced was based on the subject's ability to recover balance at the current magnitude, promoting *individualization* (Briggs et al., 2001). Variability and *randomization* of the practice conditions helped in the transfer of the learned recovery mechanisms (motor skill) to different situations (i.e., slippery floor surface), thereby promoting generalizability (Dick et al., 2000; Schmidt, 1975).

Transfer of Training

The participants came back to the laboratory the next day to test for the transfer of training. The procedure was similar to that of 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. The baseline kinematic, kinetic and EMG data were recorded before inducing the slip, representing any proactive changes in their gait. After collecting the normal walking trials, a slippery floor surface was introduced without participants' knowledge and the data were collected (Slip2). The location of the slippery surface was different from that of the moveable platform used in the training trials (Figure 2.3).

Data Analyses

The converted coordinate kinematic (marker data) and kinetic (force plate) data were low-pass filtered using a fourth order, zero lag, Butterworth filter at a cut off frequency of 7 Hz. The EMG data were digitally band pass filtered at 10-450 Hz following data collection (Chambers et al., 2007). They were then rectified and low-pass filtered using a fourth order, zero lag, Butterworth filter with a 7 Hz cut off frequency to create a linear envelope (Chambers et al., 2007; Tang et al., 1998). Heel contact (HC) and Toe off (TO) were identified from the ground reaction forces. The analyses were performed during the stance phase (HC to TO) of the slipping foot.

Dependent Variables

The dependent variables are divided into two categories. 1) Variables that describe the responses after the slip is initiated (reactive strategies) and, 2) Variables that describe characteristics at heel contact before the slip is initiated (proactive strategies).

1. Reactive Adjustments

Slip severity and outcome

Slip distance: Slip distances have been used as a measure of slip severity in numerous studies (Brady et al., 2000; Lockhart et al., 2003). Slip distance was defined as the resultant distance traveled by the slipping foot after heel contact. Slip distances were divided into two parts, slip distance I and slip distance II. Initial slip distance or SDI is indicative of severity of slip initiation. The slip-start point for the SDI was defined as the instant where the first minimum of the heel contact velocity occurs (Lockhart et al., 2000). The slip-stop point for the SDI was defined as the point where the peak horizontal heel acceleration occurs after the slip-start point (mid slip in Fig 2.6). SDI was obtained from the heel coordinates of the slipping foot using the distance between slip-start and slip-end point. Slip distance II is indicative of the behavior of the slip after the slip initiation (i.e., if it may result in a fall). SDII was defined as the distance between SDI slip-stop point (mid slip in Fig 2.6) and the point where the first maximum of the horizontal heel velocity occurs after the slip-start point (Fig 2.6) (Lockhart et al., 2003).

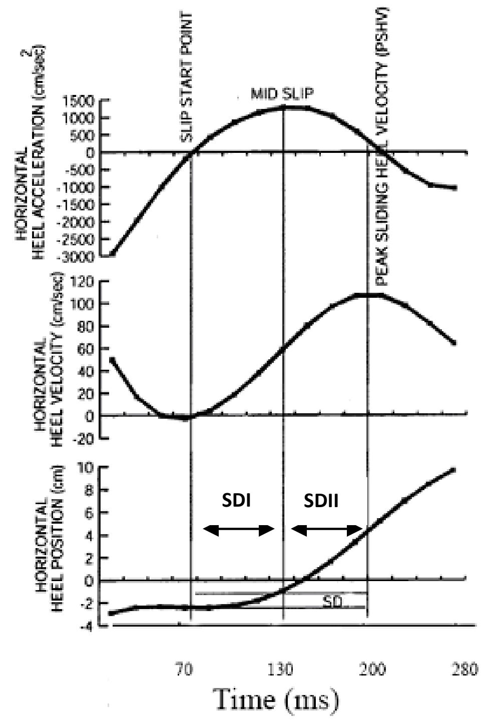

Figure 2.6 Sample profiles of the heel position, velocity and acceleration used to calculate slip distances (Lockhart et al., 2003).

Peak Sliding Heel Velocity (PSHV): The PSHV was defined as the peak heel velocity after the slip-start point (Fig 2.6). Sliding heel velocity was calculated as the instantaneous heel velocity from the slip-start point to slip-stop point (Lockhart et al., 2003). The horizontal heel velocity was obtained from the heel coordinates of the slipping foot.

Fall frequency: The outcome of the slip (i.e., fall or recovery) was measured using the fall frequency. Various parameters were utilized to detect the falls including slip distances (SDI & SDII), PSHV and motion pictures. For a slip to be considered a fall, the slip distance must exceed 10 cm and the peak sliding heel velocity must exceed the center of mass velocity while slipping (Lockhart et al., 2002). In addition, the videos for each of the participants were analyzed to detect a fall along with the trunk marker (fall to vertical minimum).

EMG measures

EMG analysis has been used to study the neuromuscular characteristics of reactions elicited in response to a slip perturbation (Lockhart et al., 2008; Chamber et al., 2007; Tang et al., 1998). Five control normal walking trials prior to the first slip were used to create the normal ensemble average profile (Chambers et al., 2007; Tang et al., 1998). Each EMG channel was peak normalized within subject using the ensemble average during the gait cycle (Kadaba et al., 1989).

Onset time: Muscle activity onsets and durations of the slipping limb were determined using a threshold of two standard deviations above activity during a quiet period of gait cycle. The onset of each muscle burst for 2 s following the heel contact was calculated using a custom built program in MATLAB 7.0.1(Mathworks, Inc., MA, USA). The presence of muscle response burst was defined as increase in muscle activity that exceeded or fell below ± 2 SD (either excitatory or inhibitory) for > 30 ms (Fig 2.7) (Lockhart et al., 2008; Tang et al., 1998). The onset and time to peak activation of MG, TA, MH and TA of the slipping limb after the slip is initiated were used in the statistical analyses.

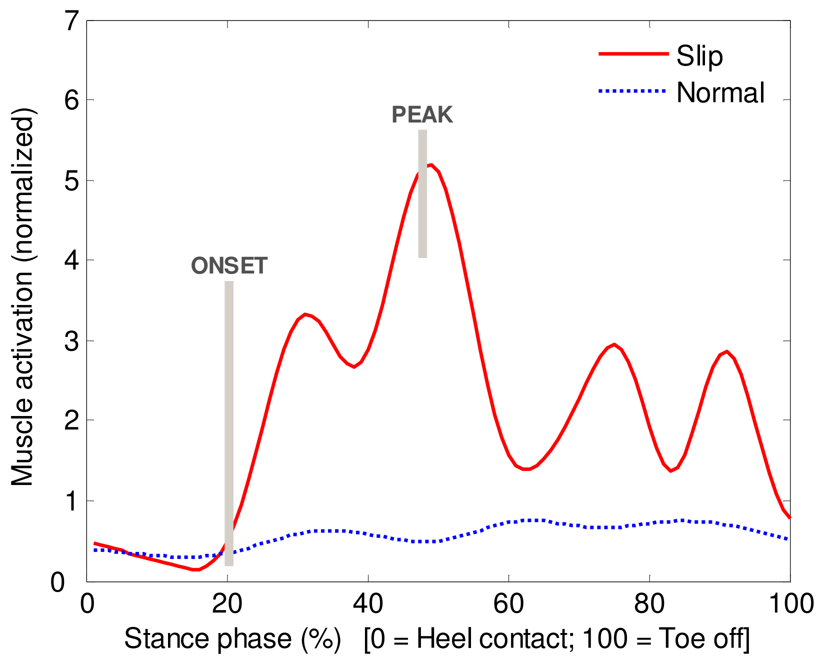

Figure 2.7 Sample EMG activation profile during normal walking and slip trial (peak normalized using ensemble average of normal gait cycle).

Muscle coactivation: The power of the EMG activity of the slipping limb was determined from the integrated EMG (iEMG), calculated by taking the integral from onset to offset, and normalized to the duration of the activation (Chambers et al., 2007). Co-contraction index (CCI) or coactivity was calculated based on the ratio of the EMG activity of the antagonist/agonist muscle pairs (TA/MG and VL/MH) using the following equation proposed by Rudolph et al. (2001). *LowerEMG* refers to the less active muscle, and *HigherEMG* refers to the more active muscle (to avoid division by zero errors). The ratio was multiplied by the sum of activity found in the two muscles. This method provides an estimate of relative activation of the pairs of muscles as well as the magnitude of co-contraction.

$$CCI = \frac{LowerEMG_i}{HigherEMG_i} \times \left(LowerEMG_i + HigherEMG_i\right)$$

The peak ankle and knee coactivity and the time to peak coactivity (ankle and knee) of the slipping limb after the slip is initiated were utilized for the statistical analyses.

Angular Kinematics

The lower extremity 2D joint angles (ankle, knee and hip) and angular velocities were calculated using methods described previously (Lockhart & Liu, 2006). Shank, thigh and upper body segments were identified from the marker position data, and the subsequent ankle, knee, hip, and trunk angles were calculated. Trunk angle was defined as angle between the trunk segment (mid-point between shoulder and mid point between ASIS) and vertical. Peak angles, angular velocity, along with time to peak angle, and angular velocities of the slipping limb and the trunk were calculated after the slip-start point. These parameters provide details about the reactive strategies employed by the participants to perform a successful recovery. All analyses were performed in the sagittal plane. Although recent empirical evidence on 3D joint moments during a reactive recovery has shown a role of hip moments in stabilizing upper body balance in the frontal plane, most of the lower extremity corrective motion is primarily in the sagittal plane (Liu & Lockhart, 2009).

Non-slipping foot measures

The quick stepping response of the non-slipping/ unperturbed foot aids in recovering from a slip by increasing the base of support (Lockhart et al., 2008; Marigold et al., 2003). The following variables were utilized to measure the response time of the non-slipping limb after the slip was initiated.

Foot onset: Foot onset (in ms) was defined as the instant when the toe vertical position of the non-slipping foot was at a maximum after toe off (TO) (Lockhart et al., 2008) (Fig 2.8).

Foot down: Foot down (in ms) was calculated as the instant when the toe vertical position of the non-slipping foot was at the first minimum after foot onset (Lockhart et al., 2008) (Fig 2.8).

Unperturbed foot reaction time: The time (in ms) between foot onset and foot down was defined as the unperturbed foot reaction time (Fig 2.8). It was analyzed to reveal how fast the non-slipping foot could substantiate its role in the recovery process after a slip perturbation (Lockhart et al., 2008).

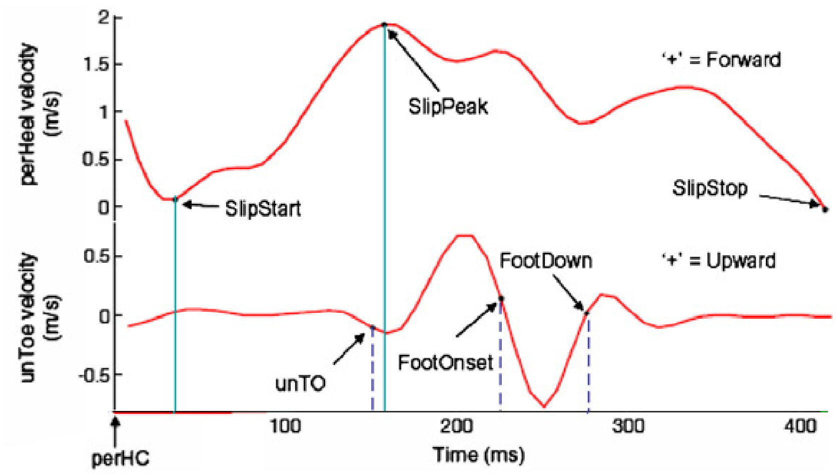

Figure 2.8 Sample heel velocity profile of the perturbed foot (per) and toe velocity of the unperturbed foot (un) indicating the responses from heel contact (HC) to toe-off (TO).

2. Proactive Adjustments

The proactive adjustments were defined as the changes in gait measures, angular kinematics, and EMG measures at heel contact before the slip is initiated. These variables were measured to quantify any anticipatory changes participants may have at heel contact from Slip1 to Slip2 session.

Gait measures

Center-of-mass velocity (COMvel): COMvel was calculated as average of all the COMs from the 14 segments as described by Lockhart et al. (2003). This included left and right feet, left and right shanks, left and right thighs, trunk, left and right hands, left and right lower arms, left and right upper arms and head. The COMvel at heel contact of the slipping foot was used for statistical analyses.

Transitional acceleration of the whole body COM (TA): TA was defined as the change in horizontal COMvel between heel contact and shortly after (~ 50ms) heel contact (Lockhart et al., 2003; Kim et al., 2005).

Required coefficient of friction (RCOF): RCOF was defined as the minimum ratio of horizontal to vertical ground reaction force (Perkins, 1978).

Angular Kinematics and EMG measures

Ankle, knee and hip angles of the slipping limb along with the trunk angle at the heel contact were used to quantify any proactive angular adjustments. The muscle (MG, TA, MH and VL) onset along with ankle and knee coactivity of the slipping limb at the heel contact was used to quantify any proactive muscular adjustments.

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 moveable platform 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. If a statistically significant main effect of training was found, subsequent univariate analysis of variance (ANOVA) was conducted to elucidate the effect of training on each of the dependent measures (reactive and proactive measures). The frequency of falls was analyzed within the groups before and after the training, and between the groups (training and control) for Slip1 (i.e., to quantify for similar fall rate at the baseline) using the chi square (χ^2) test statistic. To determine if the groups had similar slipping characteristics during Slip1, a between group one-way ANOVA was performed on slip distances (SDI & SDII) and PSHV. To determine if the gait characteristics prior to slipping during Slip1 were similar in both the groups, a between group one-way ANOVA was performed on COMvel, TA and RCOF at heel contact. All statistical analyses were conducted using SPSS 11.5.0 (Chicago, IL) with a significance level of $p < 0.05$ for all the tests. In order to verify the assumptions of MANOVA and ANOVA, all responses were evaluated for normality (using Shapiro-Wilk W test) and sphericity (using Bartlett's sphericity test). The results indicated no significant violation of assumptions.

RESULTS

The results indicate that the training group was able to successfully transfer the strategies learned during training to an actual slippery surface, and reduce their frequency of falls. The improvements in the slip outcome are distinguishable based on proactive and reactive control strategies. Changes were seen both before (proactive) and after (reactive) the slip onset during the transfer of training trials. The training group was able to reduce the frequency of falls from 42% upon the first unexpected slip (Slip1) during the baseline trial to 0% upon the second unexpected slip (Slip2) during the transfer of training trial (χ^2 *= 12.67, df = 1, p = 0.007)*. Although, the frequency of falls in the control group reduced from 50% upon the first unexpected slip (Slip1) to 25% upon the second unexpected slip (Slip2), the results were not statistically significant (χ^2 *= 1.67, df = 1, p = 0.216)*. Both training group and control group were at a similar fall rate during Slip1 (χ^2 *= 0.57, df = 1, p = 0.862)*. The MANOVA on the difference values (Slip2 – Slip1) for all the dependent variables indicated a significant effect of training [*Wilk's lambda:* $F_{(1, 18)} = 6.01$, $p = 0.009$]. Subsequent univariate analyses are as follows.

Reactive changes after slip onset

Slip severity measures

Differences in the slip outcome during the Slip2 trials were influenced by the changes in the slip severity measures between control and training groups. The ANOVA indicated that SDI and SDII decreased more from Slip1 to Slip2 in the training group compared to control [*SDI*: $F_{(1, 18)} = 12.34$, $p = 0.002$, *SDII*: $F_{(1, 18)} = 18.34$, $p = 0.001$]. Figure 2.9 indicates the difference values (Slip2 – Slip1) of SDI, SDII and PSHV between the groups. Means and standard deviations of these variables during Slip1 and Slip2 are provided in Table 2.2. The decrease in the peak sliding heel velocity was greater for the training group (Table 2.2) compared to control [$F_{(1, 18)} = 9.008$, $p = 0.008$]. No significant differences were found in the mean slip distances and peak sliding heel between the groups during Slip1 [$F_{(1, 18)} = 2.008$, $p = 0.22$], suggesting no group differences at the baseline.

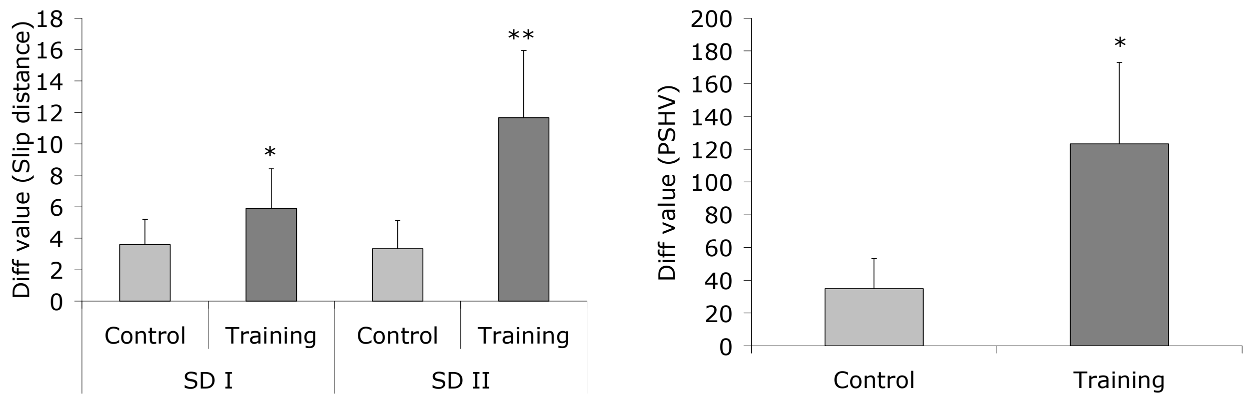

Figure 2.9 Difference values (Slip2 – Slip1) of slip distances (SDI, SDII) and peak sliding heel velocity for control and training groups (* p < 0.05, **p < 0.01)

Table 2.2 Mean ± SD of slip parameters during Slip1 and Slip2 trials between control and training group

Variable	Group			
	Training		Control	
	Slip1	*Slip2*	*Slip1*	*Slip2*
Slip distance I (cm)*	10.57 ± 4.62	4.29 ± 1.26	12.34 ± 6.34	9.36 ± 4.25
Slip distance II (cm) **	18.97 ± 6.29	7.29 ± 2.26	20.63 ± 6.25	17.29 ± 4.67
Peak sliding heel velocity (cm/s) **	218.46 ± 59.29	87.64 ± 28.29	190.63 ± 86.25	155.29 ± 75.67

Note. * $p < 0.05$, ** $p < 0.01$, p-value represent the statistics on the difference value (Slip2 – Slip1) between groups

Angular kinematics

The slipping limb (ankle, knee and hip) angles and trunk angle followed similar recovery patterns during Slip1 and Slip2 in both groups. In general, after the slip-start, forward shank rotations were reduced by sending the ankle into plantarflexion and, knee, hip and trunk into extension. During the mid-slip, recovery attempts resulted in the knee and hip flexion followed by trunk flexion, finally approaching slip-stop. The peak knee flexion [$F_{(1, 18)} = 8.26, p = 0.01$] and peak hip flexion [$F_{(1, 18)} = 15.46, p = 0.001$] decreased more from Slip1 to Slip2 in the training group compared to control (Table 2.3). The peak knee angular velocity decreased more from Slip1 to Slip2 in the training group compared to control [$F_{(1, 18)} = 9.46, p = 0.01$]. A decrease in the peak angular velocity of hip, trunk and ankle was observed but the differences were not significant between groups. The peak trunk angular velocity increased in the control group from Slip1 to Slip2 trial (Table 2.3). Further analysis revealed a significant effect of group on time to peak angular velocities. The time to peak trunk angular velocity [$F_{(1, 18)} = 11.46, p = 0.01$] and hip angular velocity [($F_{(1, 18)} = 7.45, p = 0.03$)] decreased more in the training group compared to control (Fig 2.10).

Table 2.3 Mean ± SD of joint angles and angular velocities during Slip1 and Slip2 trials between control and training group

Variable	Group			
	Training		Control	
	Slip1	*Slip2*	*Slip1*	*Slip2*
Joint angles (deg)				
Ankle angle at HC (+ = plantar)	98.23 ± 3.66	100.52 ± 4.67	95.56 ± 4.29	98.56 ± 5.29
Knee angle at HC (+ = flex)†	-5.24 ± 1.23	-3.64 ± 2.89	-2.46 ± 1.23	-1.53 ± 0.98
Hip angle at HC (+ = flex)	10.86 ± 4.23	9.54 ± 5.29	16.32 ± 5.28	18.42 ± 6.39
Trunk angle at HC (+ = flex)	9.86 ± 3.54	10.34 ± 5.56	10.34 ± 5.76	9.34 ± 3.56
Peak Ankle angle (+ = plantar)	108.60 ± 5.34	103.38 ± 4.23	110.32 ±4.55	108.87 ± 6.78
Peak Knee angle (+ = flex)**	25.63 ± 5.50	18.04 ± 3.68	24.59 ± 5.39	21.24 ± 4.38
Peak Hip angle (+ = flex)*	12.44 ± 3.96	7.61 ± 2.45	18.70 ± 3.47	16.42 ± 2.53
Peak Trunk angle (+ = ext)	31.44 ± 13.96	29.61 ± 10.45	38.70 ± 13.47	39.42 ± 12.53
Joint angular velocity (deg/s)				
Peak Ankle velocity	85.66 ± 15.96	75.66 ± 16.47	102.56 ± 22.4	95.78 ± 10.45
Peak Knee velocity*	244.34 ± 25.9	189.34 ± 16.4	255.45 ± 32.4	210.29 ± 31.6
Peak Hip velocity†	150.44 ± 22.61	75.45 ± 12.55	150.4 ± 28.65	75.45 ± 10.53
Peak Trunk velocity†	135.32 ± 13.21	115.32 ± 33.81	135.32 ± 23.2	145.32 ± 16.2

Note. * $p < 0.05$, ** $p < 0.01$, †$p < 0.1$, p-value represent the statistics on the difference value (Slip2 – Slip1) between groups

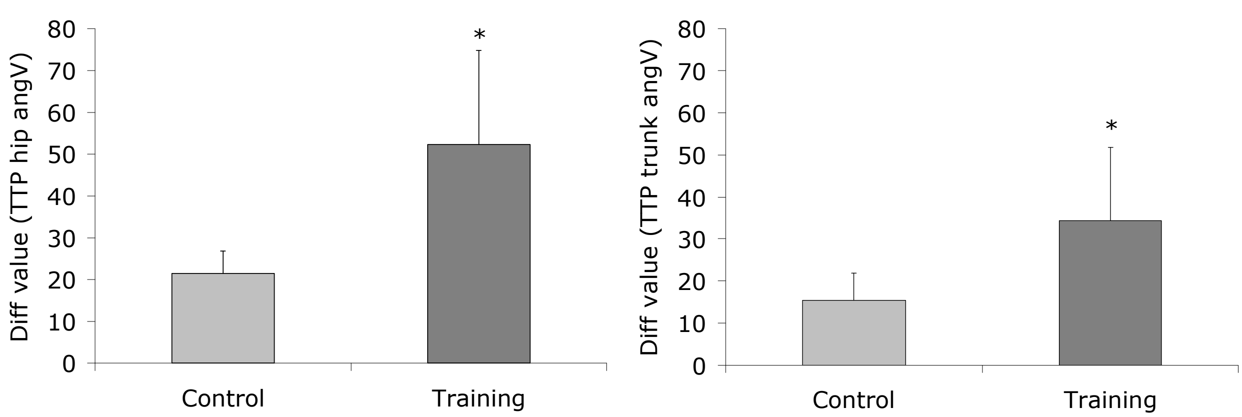

Figure 2.10 Difference values (Slip2 – Slip1) of time to peak (TTP) angular velocity (hip and trunk) between control and training group. (* p < 0.05)

EMG measures

Muscle responses of the slipping limb to Slip1 were similar in both training and control groups, with activation of medial hamstrings (MH) (~ 160 ms), followed by medial gastrocnemius (MG) (~ 180 ms), tibialis anterior (TA)(~ 188 ms), and vastus lateralis (VL) (~ 240 ms). There was an early onset of MH [$F_{(1, 18)} = 14.97, p = 0.001$] and TA [$F_{(1, 18)} = 10.46, p = 0.01$] from Slip1 to Slip2 trial in the training group compared to control. An early onset of MG and VL muscles were also observed after training, but the differences between the groups were not significant (Table 2.4). The time to peak activation of MH [$F_{(1, 18)} = 15.55, p= 0.001$] and TA [$F_{(1, 18)} = 16.52, p = 0.001$] muscles decreased more in the training group compared to control. Figure 2.11 indicates the time to peak activation during Slip1 (solid line) and Slip2 (dotted line) in all the muscles of the slipping foot in the training group.

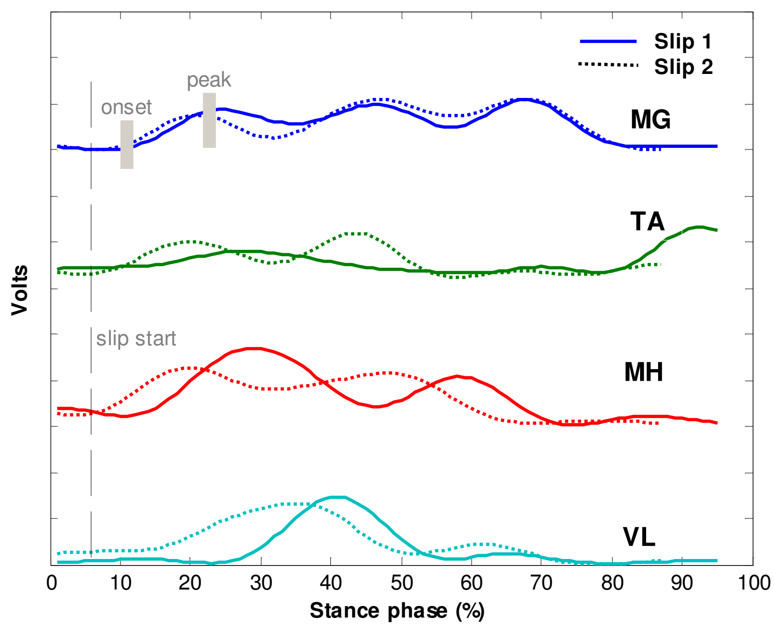

Figure 2.11 Sample muscle activation profile of medial gastrocnemius (MG), Tibialis anterior (TA), medial hamstrings (MG), and Vastus lateralis (VL), during Slip1 and Slip2 trial in the training group.

Peak knee coactivity decreased from Slip1 to Slip2 in the training group and increased in the control group. The difference value was significant in the training group compared to control [*F*

$_{(1, 18)} = 31.31, p = 0.0001]$. Similarly, peak ankle coactivity decreased from Slip1 to Slip2 in the training group and increased in the control group, however the difference value was significant in the training group [$F_{(1, 18)} = 19.46, p = 0.001$] (Table 2.4). The time to peak knee coactivity decreased more in the training group from Slip1 to Slip2 compared to control [$F_{(1, 18)} = 10.46, p = 0.01$] (Table 2.4). The time to peak ankle coactivity reduced in the training group but the differences were not statistically significant.

Table 2.4 Mean ± SD of onset of muscle activity after slip-start and the time to peak activations (recovery trials only)

Variable	Group			
	Training		Control	
	Slip1	*Slip2*	*Slip1*	*Slip2*
Muscle activation onset (ms)				
Medial gastrocnemius	188 ± 33.66	185 ± 14.67	189 ± 24.29	179 ± 25.29
Tibialis anterior*	197 ± 22.23	165 ± 12.89	188 ± 21.23	178 ±12.98
Medial hamstrings*	155 ± 11.76	133 ± 10.33	168 ± 15.28	156 ± 16.39
Vastus lateralis	238 ± 23.54	220 ± 15.56	245 ± 25.76	255 ± 15.99
Time to peak activations (ms)				
Medial gastrocnemius	335 ± 25.50	321± 23.68	364 ± 15.39	377 ± 34.38
Tibialis anterior**	312 ± 33.96	277 ± 22.45	378 ± 23.47	362 ± 32.53
Medial hamstrings**	250 ± 13.96	215 ± 17.45	290 ± 23.47	278 ± 22.53
Vastus Lateralis†	365 ± 25.35	340 ± 16.68	369 ± 33.12	354 ± 20.73
Coactivations				
Peak knee coactivity **	2.45 ± 1.12	1.77 ± 0.94	2.23 ± 1.39	2.44 ± 1.44
Peak ankle coactivity*	1.88 ± 0.96	1.32 ± 0.45	1.95 ± 1.11	2.1 ± 0.99
Time to peak knee coactivity**	310 ± 43.96	250 ± 37.15	320 ± 44.47	310 ± 29.66
Time to peak ankle coactivity†	290 ± 25.35	240 ± 36.68	319 ± 53.12	330 ± 20.55

Note. * p< 0.05, ** p < 0.01, †p <0.1, p-value represent the statistics on the difference value (Slip2 – Slip1) between groups

Non-slipping foot measures

After evaluating the slipping foot timing characteristics (slip-start, slip-peak and slip-stop), the response time of the non-slipping foot was calculated and characterized as toe-off, foot-onset, foot-down, and unperturbed foot reaction time. In general, once the slip was initiated and the slipping foot was sliding forward, a quick stepping response of the non-slipping foot resulted in successful recovery. No differences were found in the toe-off and foot-onset between the groups.

The unperturbed foot reaction time (difference between foot onset and foot down) decreased more from Slip1 to Slip2 in the training group compared to control [$F_{(1, 18)} = 10.46, p = 0.02$] (Table 2.5).

Table 2.5 Mean ± SD of the non-slipping foot response time after the slip was initiated

Variable	Group			
	Training		Control	
	Slip1	*Slip2*	*Slip1*	*Slip2*
Non-slipping foot response time (ms)				
Toe off	156 ± 29.23	149 ± 15.73	160 ± 18.66	155 ± 25.12
Foot onset	270 ± 16.24	260 ± 15.22	278 ± 20.56	285 ± 23.16
Foot down†	395 ± 25.22	368 ± 22.34	400 ± 28.34	410 ± 26.34
Unperturbed foot reaction time *	128 ± 15.22	100 ± 18.16	122 ± 20.76	126 ± 28.76

Note. * $p < 0.05$, ** $p < 0.01$, †$p < 0.1$, p-value represent the statistics on the difference value (Slip2 – Slip1) between groups

Proactive changes at heel contact before slip onset

The results indicated few proactive adjustments in the training group before the slip during the transfer of training trial (Slip2). Both training and control group had no significant differences in the walking speed during Slip1 and Slip2 trials. The COMvel at heel contact before slip-start increased more from Slip1 to Slip2 in the training group as compared to control [$F_{(1, 18)} = 10.76, p = 0.004$] (Fig 2.13). Similarly, the transitional acceleration of the whole body COM increased more in the training group compared to control [$F_{(1, 18)} = 10.34, p = 0.004$]. No significant differences were observed in the friction demand characteristics (RCOF) between Slip1 and Slip2 trials in either control or training group. No significant differences were observed in the ankle, knee, hip and trunk angle at the heel contact before the slip onset in both groups. In terms of muscle activation, participants in the training group had an early onset of MH activity around heel contact compared to the control group during Slip2 trial [$F_{(1, 18)} = 5.34, p = 0.03$]. No significant differences were found in the ankle and knee coactivity at heel contact between the groups.

Changes in proactive and reactive strategies during moveable platform training

As expected, the moveable platform training reduced the incidence of balance loss from training trial T1 to T12. There were three distinctive strategies used by participants to recover from the simulated slips (Fig 2.12). During the first block of trials, the reactive strategy was the protective stepping of the non-slipping foot posterior to the slipping foot after slip-start (Fig 2.12). During the course of the training, participants either used lateral stepping of the non-slipping foot or used the slipping foot to skate over and then used the non-slipping foot to step anterior to the slipping foot (Fig 2.12). The latter two strategies relied more on the recovery responses of the slipping foot whereas the non-slipping foot was responsible for recovery during the posterior stepping, which often lead to a balance loss.

During the first block of training trials (T1-T3), there was a 50% (6/12) incidence of balance loss that reduced to 16% (2/12) during the second block of trials (T4-T6), and to 0% by the end of the randomized trial set (T7-T12). Several proactive and reactive strategies were observed from T1 to T12 trials that led to the reduction in the balance loss and improvement in recovery.

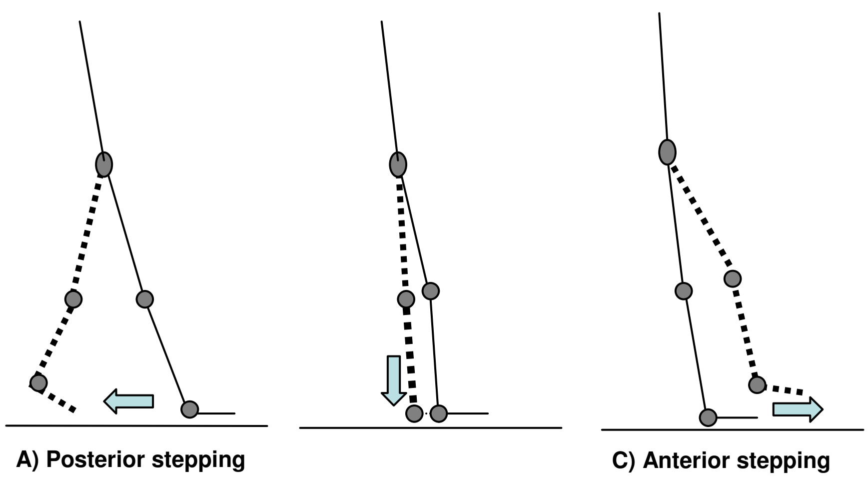

Figure 2.12 Strategies employed by the slipping foot (solid line) and non-slipping foot (dotted line) to recover from the slips during training.

In terms of proactive control, after the first training trial, participants increased their COMvel at heel contact. An increased variability was observed in the COMvel during the first two blocks of training trials (Fig 2.13). However, a learning plateau was observed by the third block of training trials (Fig 2.13). Similar pattern was observed in TA, with an initial increase after the first training trial and a plateau from T7-T12 trial (Fig 2.13). In terms of RCOF, participants walked with a reduced friction demand in anticipation of a slip during the training trials. RCOF values decreased from T1-T6, and then reached a plateau from T6-T12. Proactive changes were also observed in the angular kinematics of the slipping foot. After the first training trial, participants had an increased ankle plantarflexion and reduced hip flexion at heel contact.

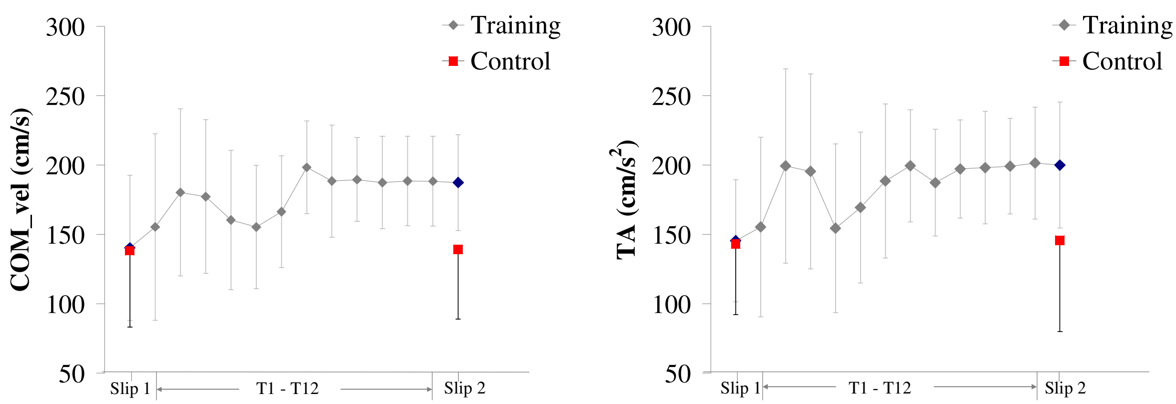

Figure 2.13 Mean ± 1 SD of center-of-mass velocity and transitional acceleration of whole body COM (TA) at heel contact from T1- T12 slip training trials (training group), and from Slip1 and Slip2 trials (control and training group).

Apart from proactive changes at the heel contact before the platform movement, various reactive responses were observed during the perturbation. In terms coactivation, an increased peak ankle and knee coactivity was observed from T1-T3 trials (Fig 2.14). In the following block of trials, peak ankle and knee coactivity reduced and a plateau was observed during T7-T12 trials. The time to peak ankle and knee coactivity increased during the first block of trials (T1-T3) and then decreased in the subsequent training trials. In terms of recovery kinematics, differences were observed in the peak hip flexion and peak knee flexion angles. During the first block of trials (T1-T3), both peak hip and knee flexion angles increased, followed by a decrease in the peak angles from T7-T12 trials. The peak ankle plantarflexion varied during the training trials and did not follow a specific pattern.

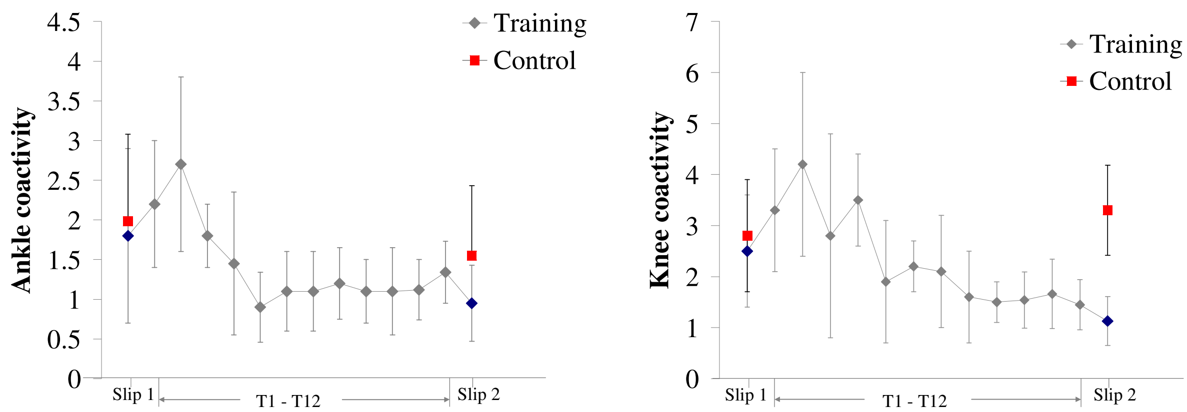

Figure 2.14 Mean ± 1 SD of peak ankle and knee coactivity from T1- T12 slip training trials (training group), and from Slip1 and Slip2 trials (control and training group).

DISCUSSION

This study examined the effects of moveable platform training in reducing fall rate and improving recovery strategies in older adults. The findings from the study lend support to the proposed hypotheses. First, the results indicated that older adults were able to learn movements related to recovery on the moveable platform, hence reducing their frequency of falls during the training. Second, older adults were able to carry over the motor skills (i.e., to resist a fall) learned during training to an actual slippery surface the next day. As hypothesized, when exposed to a slippery surface, the frequency of falls reduced in the training group compared to controls. The decreased balance loss in the training group was characterized by both proactive and reactive adaptations.

Reactive strategies during and after the training

The moveable platform training had beneficial effects in improving recovery and reducing fall frequency in the older adults. During the training, participants were able to reduce their fall frequency within 5-6 training trials and were able to maintain their balance in the subsequent perturbations. The fall frequency decreased in the training group from 42% during Slip1 to 0% during Slip2. Although, fall frequency decreased in the control group from 50% to 25%, the difference was not statistically significant. Additionally, there were two participants in the control group 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. Various reactive or feedback strategies were employed by the training group to successfully recover from a slip. The results indicated a reduction in slip displacement and peak sliding heel velocity in the training group, leading to less severe slips. Reducing the distance traveled by the slipping foot reduces the likelihood of falling (Brady et al., 2000; Strandberg & Lanshammar, 1981; Perkins et al., 1978). Greater differences were seen in the reduction of slip distance II in the training group after training, indicating an improvement in the slip recovery phase. Slips were initiated at similar time intervals in both training and control groups during Slip1 and Slip2 trials (Fig 2.15). However, time required for slip-stop was reduced in the training group as compared to the control group during the Slip2 trial. Further analysis revealed a reduction in the touch down time of the non-slipping foot after the slip initiation in the training group (Fig 2.15). The unperturbed foot reaction time was 110 ± 19.9 ms for the training group and 150 ± 29.8 ms for the control group. A quick stepping response of the unperturbed foot after slip initiation helps in the recovery process by widening the base of support (Lockhart et al., 2008; Marigold et al., 2003).

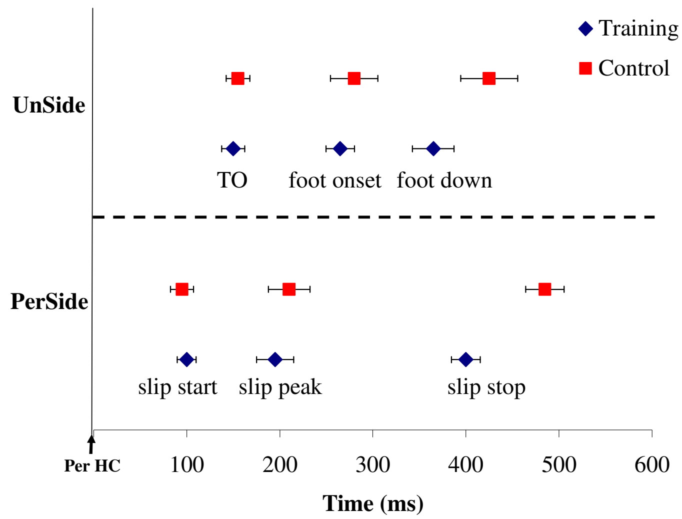

Figure 2.15 Slip events of the perturbed (PerSide) foot and the unperturbed (UnSide) foot during Slip2 trial for training and control group. The graph only contains data from successful recovery. (TO- unperturbed foot toe off, PerHC- heel contact of the slipping foot).

In terms of neuromuscular adaptations, an early onset and reduced time to peak MH and TA muscle of the slipping limb were observed in the training group during the Slip2 trial. After a slip is initiated, faster recovery reactions within 100 to 200 ms will help in stabilizing the slipping foot and avoiding a fall. The initial muscular response to a slip consists of activation of MH followed by other muscles (Chambers et al., 2007). An early activation therefore may help in stabilizing knee joint and therefore help in reducing slip displacement. During the training session, similar patterns of early onset and reduced time to peak muscle activations from T1 to T12 were observed, indicating a positive transfer to Slip2. Reactive muscle activation can be attributed to the feedback process of motor control that uses reflex pathways to modify motor-unit recruitment and continually adjust ongoing muscle activity (Swanik et al., 1997). Both proactive and reactive motor control can improve stability if the necessary sensory and motor pathways are stimulated frequently. Every time a particular signal passes through a sequence of synapses (e.g. in this study, signals to the CNS related to the perturbation); the synapses become more capable of transmitting the same signal the next time (Hodgson et al., 1994; Guyton, 1981). Frequent stimulation of the pathways, therefore, enhances reflex pathways for reactive motor control (Swanik et al., 1997). After repeated exposure to slips during the training, it may be possible that older adults were able to achieve an optimal strategy to quickly activate muscles necessary for stabilization.

Further reactive strategies observed were decreased peak knee and ankle coactivity of the slipping limb in the training group during Slip2 trial. Coactivity was defined as the ratio of antagonist and agonist muscle pairs of the ankle and knee. In general, the integrated muscle activity of all the muscles of slipping limb increased during Slip2. The activity was higher for MH and TA muscles as compared to MG and VL muscles. Such patterns of coactivity were also observed during the training, with an initial increase and subsequent decrease in the coactivity, which remained unaffected after 6-7 training trials. Coactivation of agonist and antagonist muscles is important for the regulation of joint stiffness (Simmons et al., 1988; Osternig et al., 1986). Previous studies have indicated that training induces a decrease in coactivation, which may increase net joint torque and reduce energy expenditure (Enoka, 1997; Carolan et al., 1992). The time to peak knee coactivation was reduced in the training group during the Slip2 trial. This may be attributed to the early onset and reduced time to peak MH activity after training. It may be possible that with repeated exposure to slips, the CNS chose the most effective muscle synergy organization to achieve a common goal (i.e., recovery) with the least energy expenditure.

In terms of angular kinematics, successful recoveries relied on increased peak ankle plantarflexion, knee flexion, hip flexion, and decreased peak trunk extension angles. These results are consistent with data reported in previous studies investigating slips, i.e., primary knee flexion response followed by a secondary knee extension response (Lockhart & Liu, 2006; Cham et al., 2001). Significant differences were found in the knee and hip kinematics between the groups. The peak knee flexion and hip flexion angles decreased in the training group while recovering from the Slip2 trial. During training, similar kinematic changes were observed, with a plateau by 6-7 training trials, after which participants performed the same movements to recover from the slip. The trunk angular velocity was an important predictor of a successful recovery as compared to the peak trunk angle. During Slip1, both training and control group extended their trunk at ~ 135 deg/s before they were able to recover from the slip. However, during Slip2, the training group was able to quickly reverse their forward trunk rotations while extending their trunk at ~ 110 deg/s. Reducing forward trunk rotations are believed to have a significant effect in bringing the COM of the body within stability limits (Troy & Grabiner, 2006).

Proactive strategies during and after the training

The results indicated presence of proactive or feedforward strategies during training and transfer of training trials. Feedforward adjustments were more prevalent during the training trials as compared to the transfer of training trial (Slip2). As hypothesized, participants were able to adjust their gait after few training trials to improve their pre-slip stability. Increases in the COMvel at heel contact and TA were observed as participants approached the platform during training. Under the anticipation of a perturbation while approaching the platform, participants adopted feedforward adjustments by increasing their COMvel and forward momentum, thus aiding to reduce the magnitude of perturbation. After experiencing mixed block of slips during training, a steady state for the COMvel and TA was acquired (within seven trials). Bhatt et al. (2006) found similar results in their study, where younger adults improved their pre-slip stability during training trials by increasing the COMvel with respect to base of support. Older adults in the current study took longer to achieve stability (~7-8 trials) as compared to the younger adults (~3-5 trials) in previous studies (Bhatt et al., 2006; Pavol & Pai, 2002). Similarly, during the Slip2 session, participants walked with an increased COMvel at heel contact before the slip was initiated. Increases in the COMvel aids in maintaining balance when experienced with a slip (Pai et al., 1997; You et al., 2001; Lockhart et al., 2003). During normal walking, the most hazardous phase for slip is the period right after heel contact as the body weight is being transferred to the slipping foot. If stability cannot be regained at this time, it may result in a backward fall. During this time, the whole body COM moves from behind to ahead of the base of support and any change will alter the horizontal and vertical forces (Lockhart et al., 2003), affecting slip severity. Therefore a faster COMvel at this time may help in increasing stability from backward loss of balance. Although the pace was kept constant during Slip1 and Slip2 session, further investigation indicated that participants in the training group walked with shorter stride length during Slip2 compared to Slip1, which may help in making the COMvel faster. However, the differences in the stride length were not statistically significant.

Further proactive changes were observed in early onset of MH activity at heel contact in the training group during Slip2. Similar responses were observed during training trials. There was an early onset of MG and MH of the slipping limb near heel contact during training, suggesting that participants preactivated their ankle plantarflexors and knee flexors in preparation of the perturbation. This may be related to the feedforward strategy of increased plantarflexion and knee flexion angles during heel contact. Chambers et al. (2007) reported similar findings, where younger adults preactivated their MG muscles when aware of a slippery surface. Preactivation of muscles can provide quick compensation for external loads by increasing joint stiffness and are critical for dynamic joint stability (Griller et al., 1972). In terms of angular kinematics of the slipping limb, no differences were found in the ankle, knee, hip and trunk angles at the heel contact between Slip1 and Slip2, indicating a reduced reliance on feedforward kinematic strategies.

In summary, study findings indicate that older adults were able to transfer the motor skills acquired from simulated slips on the moveable platform to a vinyl slippery surface. The training group had a better recovery performance compared to the control group, hence reducing their incidence of falls to 0% during Slip2. Improvements in the recovery performance were attributed to both proactive and reactive strategies employed by the training group. Main effects of training were found in reducing the reaction time to a slip (i.e., quicker response of the non-slipping foot, reduced slip distances, faster slip-stop) and producing effective muscle activation patterns (decreased time to peak activations, decreased time to peak coactivity), thereby reducing slip severity and fall frequency. Proactive strategies (increased COMvel, increased TA) were helpful in improving the pre-slip stability. Both control and training groups had similar characteristics during slip initiation (i.e., heel angle, walking speed, step length and friction demand characteristics). It may be concluded that, with repeated exposure to slips, adaptations to both feedforward and feedback strategies was achieved, leading to successful recovery reactions in the training group.

Several limitations exist in the current study. First, only healthy older adults were recruited in the study and it is unclear how these results may change with a different population (i.e., fall prone older adults). Second, it is difficult to generalize the results outside of the lab environment. Third, the retention of this training has not been examined and therefore it is difficult to interpret how long will the improvements last. Therefore, future studies may explore the retention of the training effects after a period of months. Future research may evaluate the transferability of this training to community and care facilities. Furthermore, future research may examine the success of this intervention in improving balance in the fall prone elderly as they are at the highest risk of non-fatal and fatal injuries. Additionally, a longitudinal study may be conducted to record fall frequencies of the individuals in this study, post training. The ultimate goal of training interventions is for older adults to transfer the motor task learned to different context outside the laboratory setting.

CHAPTER 3 – A PRELIMINARY STUDY OF PERTURBATION-BASED SLIP TRAINING USING A VIRTUAL REALITY ENVIRONMENT

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 twelve 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, kinetic, and EMG 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 proactive and reactive control strategies learned during training to the second slip trial. The proactive adjustments included increased center-of-mass velocity and increased trunk flexion at heel contact after training. Reactive adjustments included reduced time to peak activations of knee flexors, reduced knee coactivation, reduced slip displacement, reduced time to trunk flexion, and reduced trunk angular velocity after training. 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.

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 (Fortinsky et al., 2004; Sterling et al., 2001). 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 (Mansfield et al., 2007; Kannus et al., 2005). 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.

There is an emerging use of virtual reality (VR) environments to study various aspects of human balance and control (Hollman et al., 2007; Nyberg et al., 2006; Keshner et al., 2004). 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 (Sveistrup, 2004). The use of VR in balance rehabilitation follow 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 (Jeka et al., 2000; Day et al., 1997).

VR training has been applied to the rehabilitation of various motor functions in patients with vestibular disorders (Sparto et al., 2004), to improve mobility in individuals with impaired spatial abilities and, to train balance control (McComas et al., 2002; Sveistrup, 2004). Recently, VR environments have been used to promote gait training. Fung et al. (2006) used a treadmill and motion coupled VR system for gait training older adults with movement disorders. The researchers utilized various VR scenarios (corridor walking, street crossing and park stroll) with complexity levels (slower/faster walking speed), and obstacles. Study findings showed that individuals were able to control their walking speed, while experiencing a strong sense of presence in the VR environment. With repeated practice, participants were able to improve gait speed and were able to avoid obstacle collision. Similarly, Nyberg et al. (2006) demonstrated changes in walking speed and stride length, and balance reactions in individuals when exposed to an immersive VR environment (i.e., a tilting world, heavy snowfall).

Recently, VR environments were used to study fall risk in older adults (Haibach et al., 2008). It was found that visual motion induced postural response in the older adults and they responded more strongly compared to younger counterparts. The older adults illustrated greater joint angle displacements in the joints of the lower limb. These results indicate a strong influence of visual feedback in older adults to maintain balance (Haibach et al., 2008). In general, older adults tend to rely more on visual feedback for postural control and recovering from a slip-induced fall (Lockhart et al., 2005; Sekuler 1992). Similarly, Bugnariu et al. (2007) observed that when the virtual environment was manipulated to provide distorted visual perception, older adults took more steps to maintain upright stance and had delayed onset of muscle activity. This may be due to the impairments of sensory organization in older adults (Bugnariu et al., 2007; Holden et al., 1999). Additionally, older adults initiated balance reactions by activating their neck muscles first, suggesting an excessive reliance on visual inputs or need for head stabilization. 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 (Bugnariu et al., 2007). Hollman et al. (2006) evaluated the effects of walking in a VR environment on various gait variability parameters in younger adults. Walking in the VR environment reduced stride lengths, increased step widths, and increased variability in stride velocity in younger adults. 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 (Hollman et al., 2007; Nyberg et al., 2006; Keshner et al., 2004). However, no current VR training is available that aims to improve recovery reactions in older adults. Based on previous findings, if a VR environment is created to induce repeated virtual slips via visual-vestibular conflict, individuals may elicit recovery responses (i.e., increased muscle activations, trunk flexion) similar to an actual slip. 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 main objective of the study was to design a virtual reality training to induce perturbation in older adults similar to a slip and examine the effect of the training in reducing fall frequency in older adults. The specific aims for the study were: 1) 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 and neuromuscular changes during the VR training trials, 3) To compare gait variability between normal treadmill walking and VR treadmill walking.

METHOD

Participants

Twenty-four healthy older adults (> 65 years, 12 male, and 12 female), were recruited for the study from the local Blacksburg community. The participants' demographics are presented in Table 3.1. Written consent form approved by the Institutional Review Board (IRB) of Virginia Tech was obtained from the participants before participation. Exclusionary criteria included cardiovascular, respiratory, neurological, and musculoskeletal abnormalities as well as any other difficulties hindering normal gait (Appendix A). Additionally, a physician screened participants for lower extremity (ankle, knee, hip, heel and toe) range of motion, and any balance related problems (i.e., Rhomberg, light touch test). Participants were divided into a control group (n = 12), and a virtual reality training (VRT) group (n = 12). Both training and control groups experienced two slip sessions (Slip1 and Slip2) on a slippery vinyl floor, separated by a repeated virtual slip training session for the VRT group and a walking session for the control group.

Table 3.1 Participants demographics (Mean ± SD)

	Group		
	Control (n = 12)	Training (n =12)	P value
Age (yrs)	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

Note. The P value represents the results of a t test comparing two-groups

Prior to testing, each participant completed a visual acuity test (Snellen's chart) (Appendix B) and a questionnaire on the symptoms of cyber sickness using the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993) (Appendix C). The visual acuity test was performed to evaluate if the participants could see clearly in the virtual reality environment that was displayed using a head mounted display at a distance of 1.2 m. 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

Virtual reality training set-up

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 3.1). 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 gm) and had a resolution of 832(H) x 624(V). Foam blinders attached to the HMD blocked any peripheral vision of the external environment. A regular downtown VR scene was generated (Fig 3.2) 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. The virtual slip consisted of perturbations (tilts) in the pitch plane of the VR scene at random intervals. The laboratory lights were turned off during the training trials.

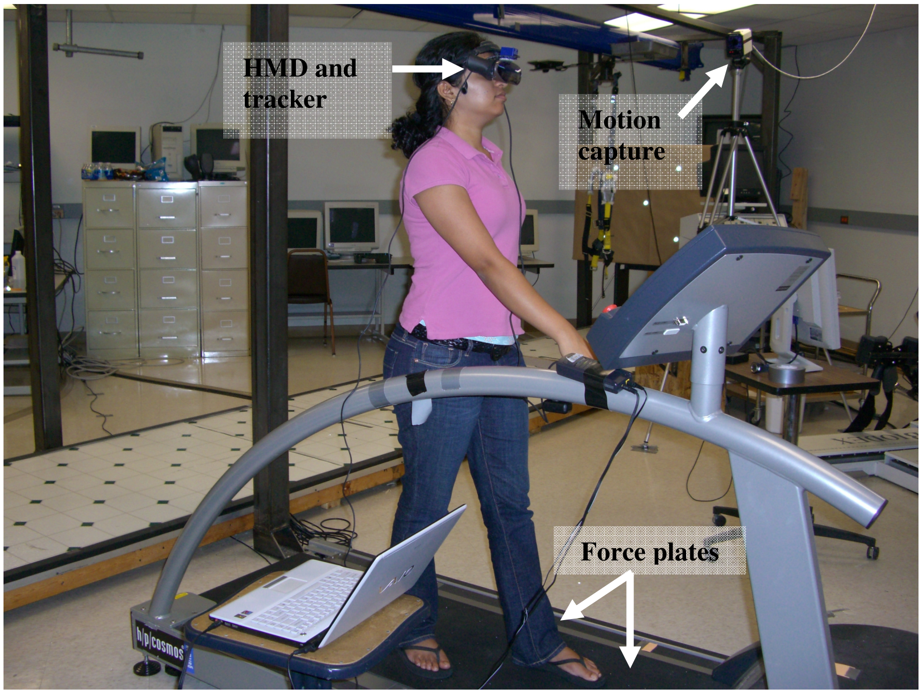

Figure 3.1 Experimental set-up of the virtual reality training including the treadmill and the head mounted display (HMD) along with the tracker and the motion capture system.

Figure 3.2 Virtual scene displayed on the head mounted display (the flow speed was matched to the speed of the treadmill).

Actual slip-perturbation set-up

The slip trials were conducted on 15 m long walkway. The walkway was embedded with two force plates (Type 45550-08, Bertec Corporation, USA) which were used to record gait characteristics. The experimental layout is shown in Figure 3.3. The slippery surface (i.e., top of one the force plates (F2)) was covered with a 1:1 water and jelly mixture to reduce the coefficient of friction (COF) (dynamic COF = 0.12) of the floor surface. Participants were unaware of the position of this surface as the force plates were covered with the same vinyl as the walkway. This is a standardized protocol used in several previous slip and fall studies (Lockhart & Liu, 2006; Lockhart et al., 2005).

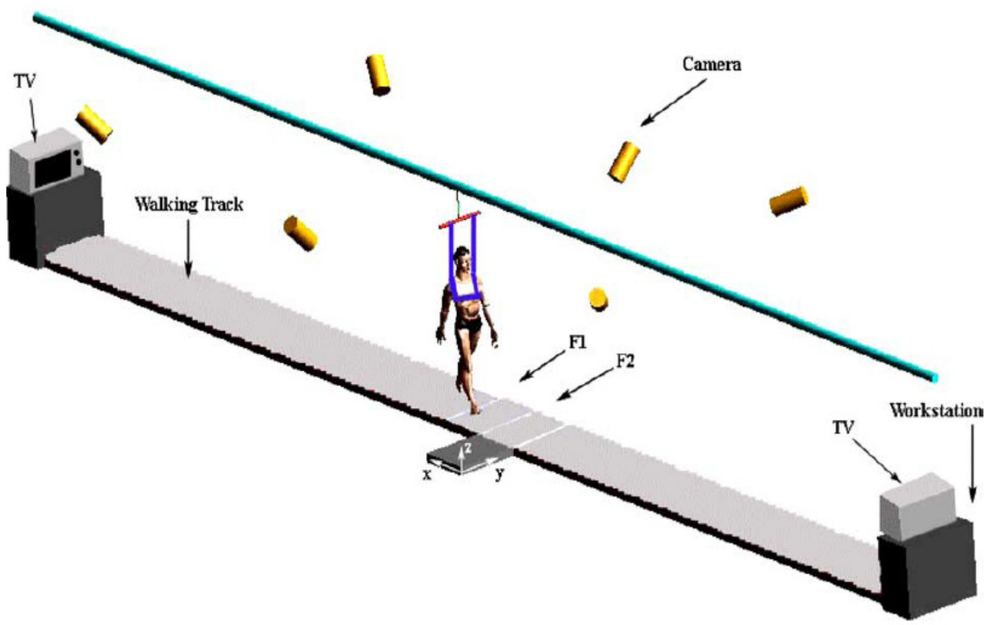

Figure 3.3 Experimental set-up for the baseline and transfer of training session including the walkway, two force plates (F1 and F2), and a six camera motion capture system.

Measurement

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 (Lockhart et al., 2003). Kinetic data were collected at 1000 Hz from the force plates on the walkway. An eight-channel EMG telemetry Myosystem 2000 (Noraxon, USA), was used to record bilateral temporal activations from vastus lateralis (VL), medial hamstring (MH), tibialis anterior (TA), and medial gastrocnemius (MG) muscles of the lower extremity. The EMG data were sampled at 1000Hz. The force plates and EMG system were connected to a 16 bit, 64 analog-input, DAQ card (PCI-6031E, 100kS/s, NI, USA). The data collection from the Qualysis, force plates, and EMG system was synchronized using a LabVIEW program. Participants wore a full body fall-arresting harness throughout the experiment (Lockhart et al., 2003) (Fig 3.3). Uniform clothes and 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 3.4). All participants underwent a slip trial on the slippery floor surface that served as a baseline measure (Slip1) during the first session. After two weeks, 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).

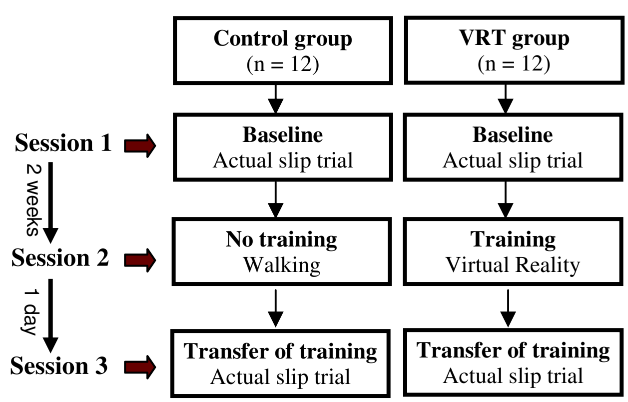

Figure 3.4 Experimental protocol for control and training group.

Baseline Measure: Session 1

After attaching the markers and the EMG electrodes, participants were instructed to walk on the walkway for 10 minutes 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 used in subsequent sessions). The starting point of their walking was adjusted so that their right foot lands on the second force plate, which was switched to a slippery surface later. The baseline kinematic, kinetic, and EMG data were recorded from five normal walking trials before inducing the slip. Participants were instructed to maintain their balance and continue walking even if they experience a slip. After collecting the normal walking trial, an actual slippery surface was introduced without participants' knowledge and the data were collected to represent Slip1. Both groups underwent the Slip1 session.

Training Acquisition: Session 2

The control group underwent normal walking trials during their second session. After attaching the markers and the electrodes, participants were instructed to walk on the track for 10-15 min. Every time participants reached the end of the track, they were instructed to perform simple filing tasks (i.e., separating different color sheets) that were arranged at both ends of the track. Data was collected from three normal walking trials during the experiment (Fig 3.5).

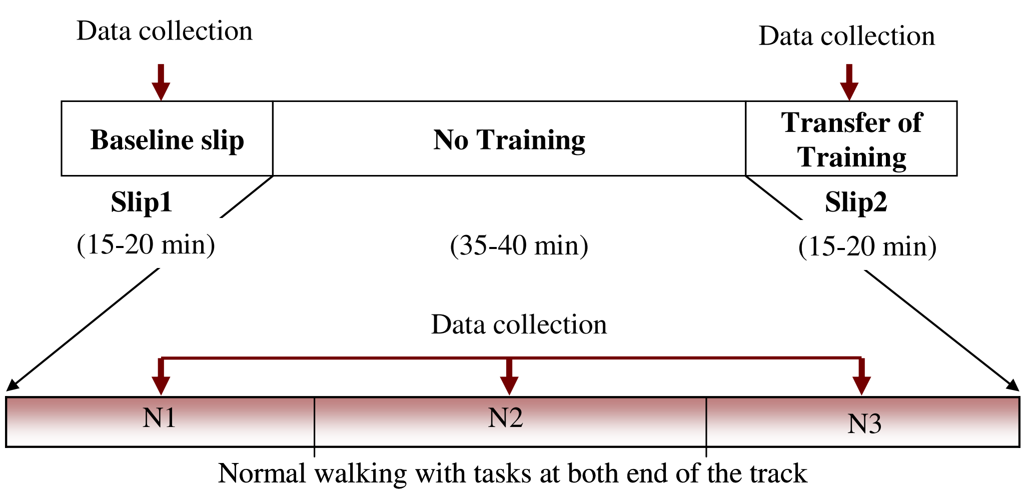

Figure 3.5 Experimental protocol for the control group.

The training group underwent virtual reality training in their second session. Participants were instructed to fill out the simulator sickness questionnaire (SSQ) (Kennedy et al., 1993) (Appendix B) to get their baseline cyber sickness scores. Following this, participants walked on the treadmill at a self-selected pace for 5 minutes wearing the harness. The initial baseline gait data (kinematic and EMG) 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 (Figure 3.3). 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 of participants). Participants were instructed to walk for 15 minutes 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, data were collected at 5, 10, and 15 min to represent walking on the treadmill with VR (VR1, VR2, and VR3) (Fig 3.6). 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 º to 25 º in the pitch plane at 60º/s. The virtual slip was manually induced by pressing a key on the computer at random intervals, during the heel contact of the right foot. This perturbation velocity and the displacement 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.

Due to limited literature 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 (Bhatt et al., 2006). The training paradigm was designed to include principles known to enhance motor learning such as variability and randomization (Dick et al., 2000; Schmidt, 1975), progressive overload (Drowatzky et al., 1999), and individualization (Briggs et al., 2001).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. 3.6). After the first block of repeated slips, the speed of the virtual scene tilt was increased or decreased by 12º/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). 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 (Kottke et al., 1978; Mansfield et al., 2007). The last 12 trials included two slip velocities (from block 1 and 2) and no slip trials presented in a random order.

Whole body kinematics, SSQ, and EMG data were recorded during all trials to represent T1-T12 (Fig 3.6). Data were also collected after end of block 1 and block 2 to represent normal walking with VR on the treadmill (VR4 and VR5) (Fig 3.6). 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.

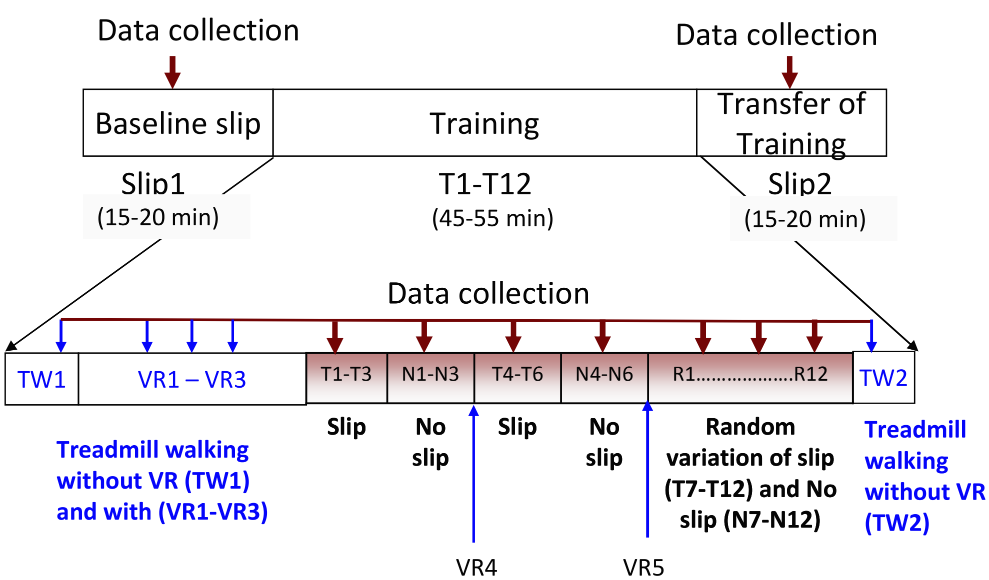

Figure 3.6 Experimental protocol for the virtual reality training group.

Transfer of Training: Session 3

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. Session 3 was performed on a separate day to avoid any confounding effects due to cyber sickness. The transfer of training 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, kinetic, and EMG 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 (Lockhart et al., 2003). The EMG data were digitally band pass filtered at 10-450 Hz (Chambers et al., 2007), following which they were rectified and low-pass filtered using a fourth order, zero lag, Butterworth filter with a 7 Hz cut off frequency to create a linear envelope (Chambers et al. 2007; Tang et al., 1998). 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.

Dependent Variables

1. Gait changes in VR environment

To quantify gait changes while walking on the treadmill with VR, angular kinematics (ankle, knee, hip, and trunk), muscles activations (MG, TA, MH, VL), and gait variability was assessed from the data that were collected at different time intervals (5, 10, 15, 20, 25 min). The lower extremity 2D sagittal angles were calculated using the marker data (Lockhart & Liu, 2006). Trunk angle was defined as the angle between the trunk segment (mid point between shoulder and mid point between ASIS) and vertical. Muscle activity onsets of the slipping limb were determined using a threshold of two standard deviations above activity during a quiet period of gait cycle. Ten gait cycles from the normal treadmill walking were used to create a normal ensemble average profile due to the variability in gait during locomotion (Lee et al., 2008;

Murray et al., 1985). Each EMG channel was peak normalized within subject using the ensemble average (Kadaba et al., 1989). The presence of muscle response burst is defined as increase in muscle activity that exceeded or fell below ± 2 SD (either excitatory or inhibitory) for > 30 ms (Lockhart et al., 2008; Tang et al., 1998). Parameters 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 (Maki et al., 1997; Menz et al., 2003; Owings et al., 2004). 1) Stride length (cm) was calculated as the anterior-posterior distance from initial heel contact to the subsequent heel contact of the same foot. 2) Stride time (ms) was defined as the duration over which the stride occurs. 3) Stride velocity (cm/s) was calculated as the ratio of stride length to stride time. 4) Step width (cm) was defined as the mediolateral distance between the right and the left heel during double stance of the gait cycle. 5) Variability in all of the above parameters was calculated as percentage coefficient of variation (% CoV). For variability calculations, 60 strides (~ 1min walking on the treadmill) were chosen and then the mean and SD was calculated across all participants.

2. Proactive and reactive changes due to training

To quantify the effects of training, dependent variables were categorized as proactive responses that occur at the heel contact before the slip is initiated, and reactive responses that occur after the slip is initiated in the stance phase (HC to TO).

Reactive responses

Slip severity and outcome

Slip distances (SDI & SDII) indicative of severity of slips were calculated using the distance travelled by the slipping heel from slip-start to slip-end (Lockhart et al., 2003) 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 (Lockhart et al., 2003). Various parameters were utilized to detect the falls including slip distances, sliding heel velocity, and motion pictures. For a slip to be considered a fall, the slip distance must exceed 10 cm and the peak sliding heel velocity must exceed the COMvel while slipping (Lockhart et al., 2002). In addition, the videos for each of the participants were analyzed to detect a fall along with the trunk marker (fall to vertical minimum). All falls detected in the study satisfied both criteria (video and data).

EMG Measures

The onset activation and the time to peak activation of muscles of the slipping limb (MG, TA, MH, and VL) were used for statistical analyses. The onset activity was determined as described before using a threshold of two standard deviations above activity during a quiet period of gait cycle. Five control normal walking trials prior to the first slip were used to create the normal ensemble average profile (Chambers et al., 2007; Tang et al., 1998). Each EMG channel was peak normalized within subject using the ensemble average (Kadaba et al., 1989). Peak ankle and knee coactivity, and time to peak ankle and knee coactivity after the slip is initiated were used to quantify effects of training. The power of the EMG activity was determined from the integrated EMG (iEMG), calculated by taking the integral from onset to offset, and normalized to the duration of the activation. Coactivity index was calculated based on the ratio of the EMG activity of the antagonist/agonist muscle pairs (TA/MG and VL/MH) using the equation proposed by Rudolph et al. (2001). *LowerEMG* refers to the less active muscle, and *HigherEMG* refers to the more active muscle (to avoid division by zero errors). The ratio was multiplied by the sum of activity found in the two muscles. This method provided an estimate of relative activation of the pairs of muscles as well as the magnitude of coactivity.

$$CI = \frac{LowerEMG_i}{HigherEMG_i} \times \left(LowerEMG_i + HigherEMG_i\right)$$

Angular Kinematics

Peak angles, angular velocity, time to peak angle, and time to peak angular velocities of the slipping limb were calculated to quantify the effect of training on angular kinematics. The lower extremity 2D joint angles (ankle, knee, and hip) and angular velocities were calculated using methods described previously (Lockhart & Liu, 2006). These parameters provide details about the reactive strategies employed by the participants to perform a successful recovery.

Non-slipping foot measures

The quick stepping response of the non-slipping/unperturbed foot aids in recovering from a slip by increasing the base of support (Lockhart et al., 2008; Marigold et al., 2003). The unperturbed foot reaction time was used to assess how fast the non-slipping foot could substantiate its role in the recovery process after a slip perturbation (Lockhart et al., 2008). The unperturbed foot reaction time was defined as the time (in ms) between foot onset and foot down (Fig 3.7). Foot onset (in ms) was defined as the instant when the toe vertical position of the non-slipping foot was at a maximum after toe off (TO) (Lockhart et al., 2008) (Fig 3.7). Foot down (in ms) was calculated as the instant when the toe vertical position of the non-slipping foot was at the first minimum after foot onset (Lockhart et al., 2008) (Fig 3.7).

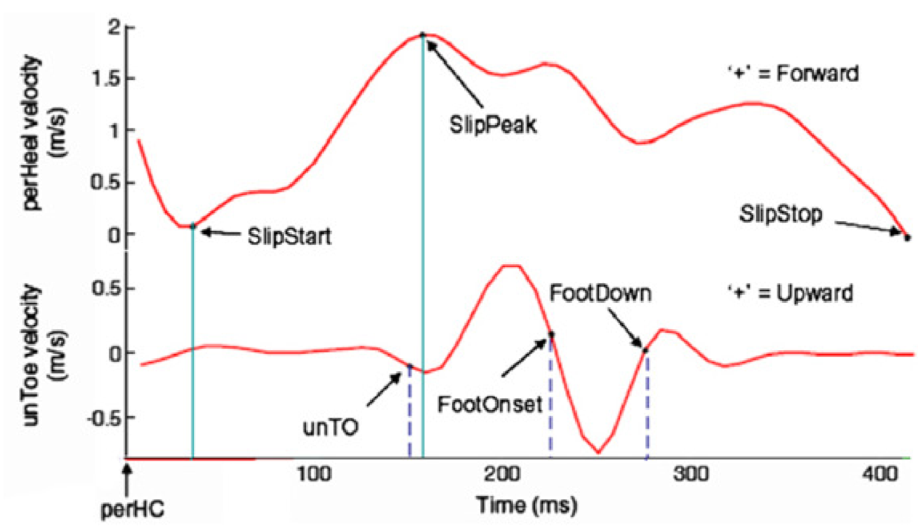

Figure 3.7 Sample heel velocity profile of the perturbed foot (per) and toe velocity of the unperturbed foot (un) indicating the responses from heel contact (HC) to toe-off (TO).

Proactive Responses

Proactive responses were defined as gait changes at the heel contact before the slip is initiated. COMvel at heel contact was calculated by taking an average of all the COM's from the 14 segments as described by Lockhart et al., (2003). Transitional acceleration of the whole body (TA) was defined as the change in horizontal COMvel between heel contact and shortly after (50 ms) heel contact (Kim et al., 2005; Lockhart et al., 2003). Required coefficient of friction

(RCOF) was defined as minimum ratio of horizontal to vertical ground reaction force (Perkins, 1978). Ankle, knee, hip and trunk angles were calculated at the heel contact to quantify changes in angular kinematics before the slip was initiated. The muscle (MG, TA, MH and VL) onsets of the slipping limb along with ankle and knee coactivity at the heel contact were used to quantify any proactive muscular adjustments.

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. If a statistically significant main effect of training was found, subsequent univariate analysis of variance (ANOVA) was conducted to elucidate the effect of training on 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 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 gait measures (COMvel, TA, and RCOF at heel contact), and slip measures (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. In order to verify the assumptions of MANOVA and ANOVA, all of the data were 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

The results indicate that the training group was able to transfer the strategies learned during training to an actual slippery surface and reduce their frequency of falls. The improvements in the slip outcome are distinguishable based on proactive and reactive control strategies. Changes were seen before (proactive) and after (reactive) the slip onset during the transfer of training trials. Additionally, participants were able to reduce their gait variability after walking in the VR environment for 15-20 min. The gait characteristics and the neuromuscular responses mimicked normal walking responses on the treadmill after the habituation period (15- 20 min). The results of the gait changes in the VR environment are presented first, followed by the results of the training.

Gait changes in virtual reality environment

A repeated measure ANOVA was performed to examine differences in gait variability while walking on the treadmill with and without VR. Analysis was performed on the data that were collected from treadmill walking before VR (TW1) and during VR (VR1 - 5 min, VR2 - 10 min, VR3 - 15 min, VR4 - 20 min, VR5 - 25 min).

General trends of angles during overground walking and treadmill walking with and without VR are presented in Figure 3.8. The figure indicates that participants walked with an increased ankle plantarflexion, increased knee flexion and trunk flexion at heel contact on the treadmill as compared to overground walking (Fig 3.8). In addition, participants further increased their ankle plantarflexion [$F_{(6, 76)} = 9.56, p = 0.02$], trunk flexion [$F_{(6, 76)} = 12.56, p = 0.001$], and decreased their knee flexion [$F_{(6, 76)} = 10.56, p = 0.02$] at heel contact in the VR environment (Fig 3.8). Post-hoc results indicated no significant differences in the angles between the last trial of VR walking (VR5) and TW1. The muscle activation profiles during the stance phase on the treadmill with and without VR are presented in Figure 3.9. In general, participants walked with an early activation of MG, TA, MH, and VL muscles at the heel contact during VR walking compared to the treadmill walking. Significant differences were only seen in the activation of VL [$F_{(6, 76)} = 9.86, p = 0.02$] and TA [$F_{(6, 76)} = 10.48, p = 0.01$] muscles between VR5 and TW1. No significant differences were observed in the activation of MG and MH muscles between VR walking and treadmill walking.

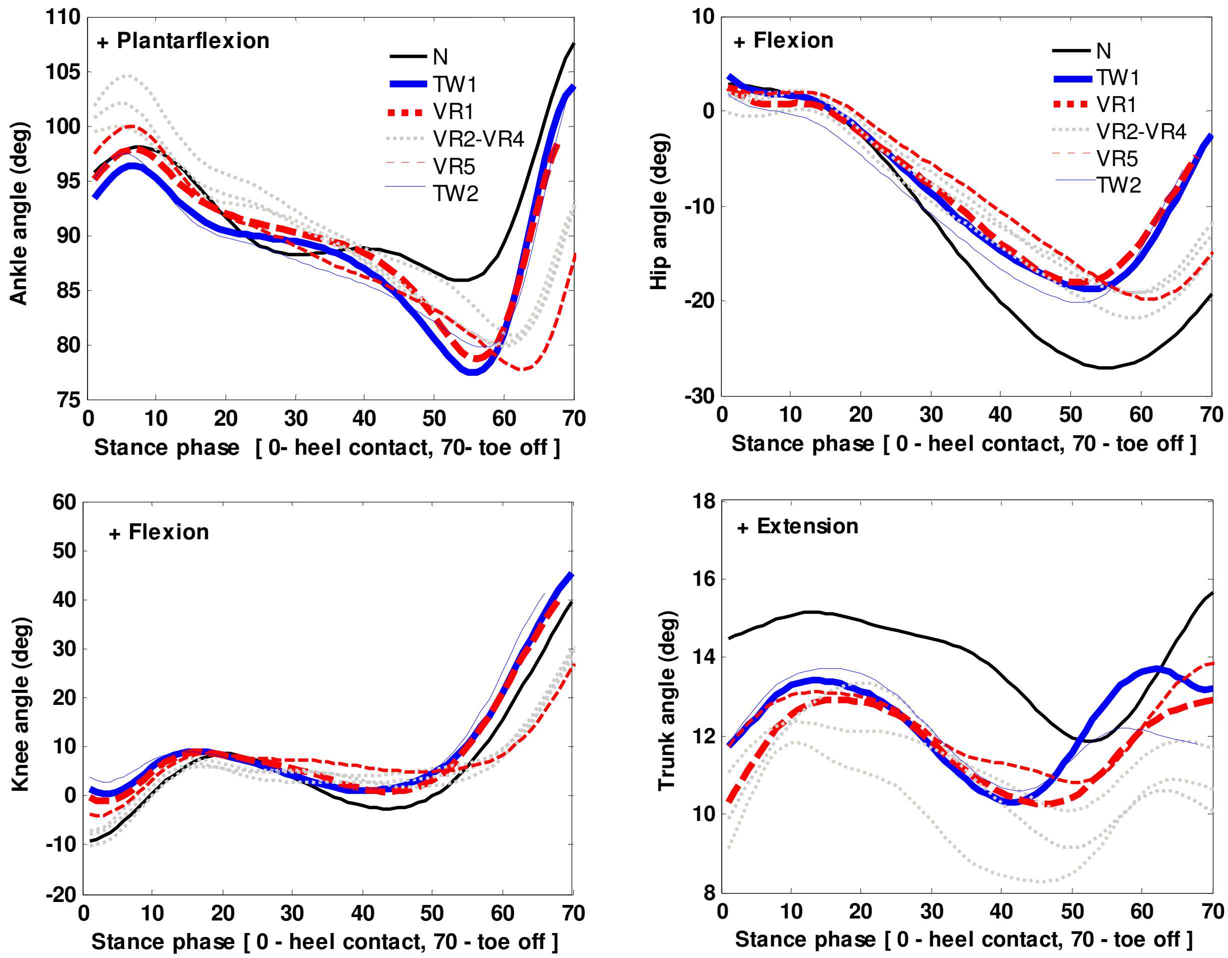

Figure 3.8 Ensemble averages of angles (ankle, knee, hip, and trunk) during normal walking (N), treadmill walking without virtual reality (TW1), walking with virtual reality (VR1 - 5 min, VR2 - 10 min, VR3 - 15 min, VR4 - 20 min, VR5 - 25 min) and treadmill walking after training (TW2). 2D sagittal angles were calculated and averaged over five gait cycles (stance phase) for each condition represented.

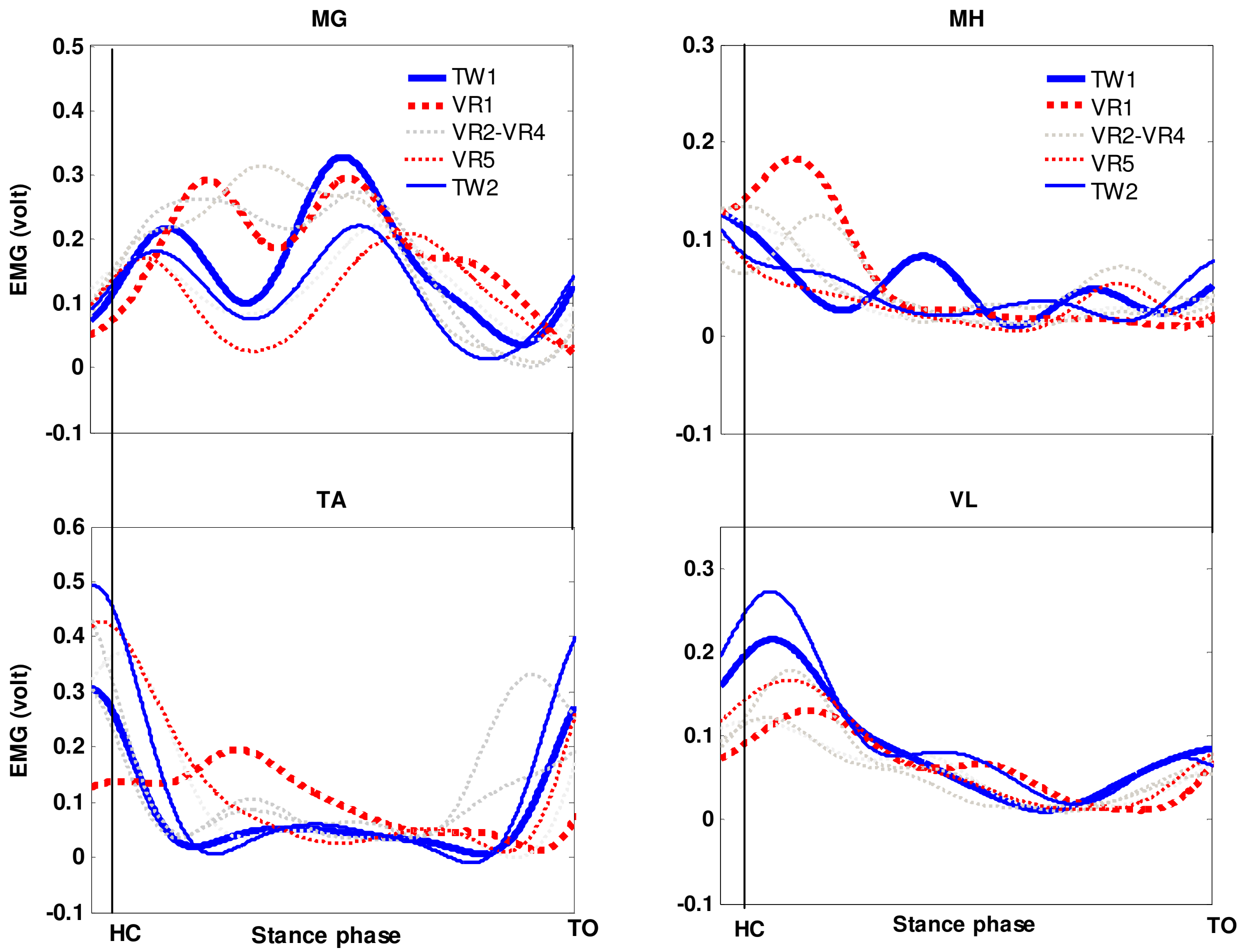

Figure 3.9 Ensemble average of muscle activation profile of medial gastrocnemius (MG), tibialis anterior (TA), medial hamstring (MH), and vastus lateralis (VL) during normal treadmill walking (TW1), walking with virtual reality (VR1 - 5 min, VR2 - 10 min, VR3 - 15min, VR4 - 20min, VR5 - 25min), and treadmill walking after training without (TW2).

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), and then increased by VR4, which remained unchanged at VR5. 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 3.10), 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.

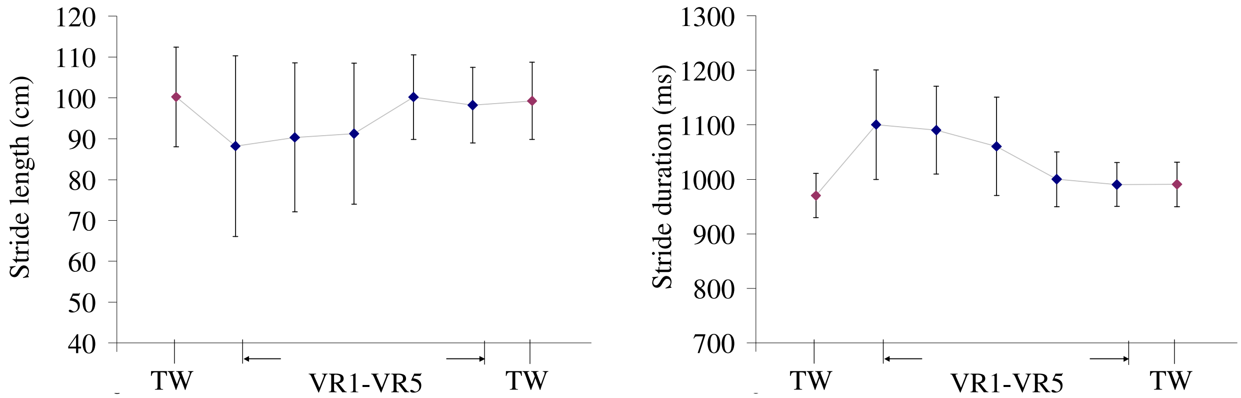

Figure 3.10 Mean ± 1 SD of stride length and stride duration during normal treadmill walking trials (TW1), walking with virtual reality (VR1 - 5 min, VR2 - 10 min, VR3 - 15 min, VR4 - 20 min, VR5 - 25 min), and treadmill walking after training (TW2). (n = 12 participants, average of 1 min walking trials (~ 60 strides)).

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- VR5 trials (Table 3.2), 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 3.2). Variability in step width increased by 21% after walking in the VR for 5 min (Table 3.2), and then reduced from VR2-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-VR5, being at the same level as TW1 at VR5 (Table 3.2).

Table 3.2 Mean ± 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 ± 2.23	4.78 ± 1.23	5.23 ± 1.78	33.78 ± 10.23
VR1 - 5 min	20.17 ± 9.34	9.12 ± 3.25	9.63 ± 3.55	42.76 ± 12.34
VR2 - 10 min	18.88 ± 7.56	8.67 ± 3.19	7.19 ± 2.88	41.67 ± 10.33
VR3 - 15 min	17.17 ± 6.34	6.08 ± 2.66	7.98 ± 1.98	39.33 ± 10.23
VR4 - 20 min	10.31 ± 5.34	5.21 ± 1.88	6.22 ± 1.23	38.23 ± 11.48
VR5 - 25 min	10.39 ± 3.45	4.23 ± 2.12	5.92 ± 1.91	37.66 ± 10.45

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.

Slip severity measures

Differences in the slip outcome during Slip2 trials were influenced by the changes in the slip severity measures. The ANOVA indicated that SDI and SDII decreased more from Slip1 to Slip2 in the VRT group compared to control [*SDI*: $F_{(1, 18)} = 10.34$, $p = 0.01$; *SDII*: $F_{(1, 18)} = 5.27$, $p = 0.03$] (Fig 3.11). Table 3.3 provides the means and standard deviations of the slip distances for the two groups. The decrease in the peak sliding heel was greater for the VRT group (Table 3.1) compared to control [$F_{(1, 18)} = 4.54$, $p = 0.05$]. 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.

Table 3.3 Mean ± SD of slip parameters during Slip1and Slip2 trials between control and training group

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

Note. * p< 0.05, p-value represent the statistics on the difference value (Slip2 – Slip1) between groups

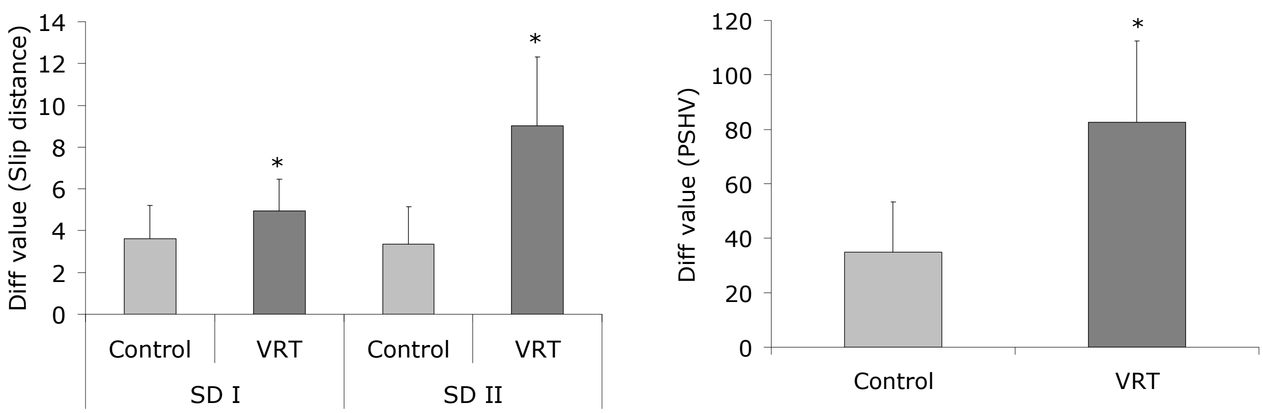

Figure 3.11 Difference values (Slip2 – Slip1) of slip distances (SDI, SDII) and peak sliding heel velocity between control and training group (* p < 0.05, ** p < 0.01).

Angular kinematics

The ANOVA indicated no significant differences in the peak ankle angle between groups. There was a decrease in the peak knee flexion and peak hip flexion angle in the VRT group compared to control, but the differences were not significant (Table 3.4). The peak ankle, knee, and hip angular velocity after slip-start, decreased from Slip1 to Slip2 trials in both VRT and control group, but no significant differences were observed between groups.

Table 3.4 Mean ± SD of joint angles and angular velocities during Slip1 and Slip2 trials between control and training group

Variable	Group			
	Training		Control	
	Slip1	*Slip2*	*Slip1*	*Slip2*
Joint angles (deg)				
Ankle angle at HC (+ = plantar) †	97.25 ± 5.66	102.52 ± 4.67	95.56 ± 4.29	98.56 ± 5.29
Knee angle at HC (+ = flex)	-2.35 ± 3.23	-2.85 ± 2.89	-2.46 ± 1.23	-1.53 ± 0.98
Hip angle at HC (+ = flex)	13.78 ± 6.23	12.03 ± 5.29	16.32 ± 5.28	18.42 ± 6.39
Trunk angle at HC (+ = ext) †	14.64 ± 4.54	10.34 ± 5.56	10.34 ± 5.76	9.34 ± 3.56
Peak Ankle angle (+ = plantar)	104.60 ± 6.22	105.38 ± 4.26	110.32 ±4.55	108.87 ± 6.78
Peak Knee angle (+ = flex)	30.23 ± 8.45	23.04 ± 8.68	24.59 ± 5.39	21.24 ± 4.38
Peak Hip angle (+ = flex)	15.44 ± 6.96	12.61 ± 5.45	18.70 ± 3.47	16.42 ± 2.53
Peak Trunk angle (+ = ext)*	35.44 ± 13.96	28.61 ± 10.45	38.70 ± 13.47	39.42 ± 12.53
Angular velocity (deg/s)				
Peak Ankle velocity	89.66 ± 12.16	90.66 ± 16.47	102.56 ± 22.4	95.78 ± 10.45
Peak Knee velocity	250.34 ± 35.9	219.34 ± 26.4	255.45 ± 32.4	210.29 ± 31.6
Peak Hip velocity†	160.44 ± 22.61	125.45 ± 32.55	150.4 ± 28.65	75.45 ± 10.53
Peak Trunk velocity*	130.32 ± 13.21	100.32 ± 23.81	135.32 ± 16.2	145.32 ± 23.2

Note. * $p< 0.05$, ** $p < 0.01$, † $p <0.1$, p-value represent the statistics on the difference value (Slip2 – Slip1) between groups

A significant effect of training was found in the peak trunk extension after slip-start [$F_{(1, 18)} = 12.46, p = 0.01$]. Peak trunk extension decreased more from Slip1 to Slip2 in the VRT group compared to control (Fig 3.12). The peak trunk angular velocity decreased more from Slip1 to Slip2 in the VRT group compared to control [$F_{(1, 18)} = 10.46, p = 0.01$] (Fig 3.12). Further analysis revealed a significant effect of group on time to peak angular velocities. The time to peak trunk velocity [$F_{(1, 18)} = 10.46, p = 0.02$] and hip angular velocity [$F_{(1, 18)} = 6.45, p = 0.03$] decreased more from Slip1 to Slip2 in the VRT group compared to control (Fig 3.13).

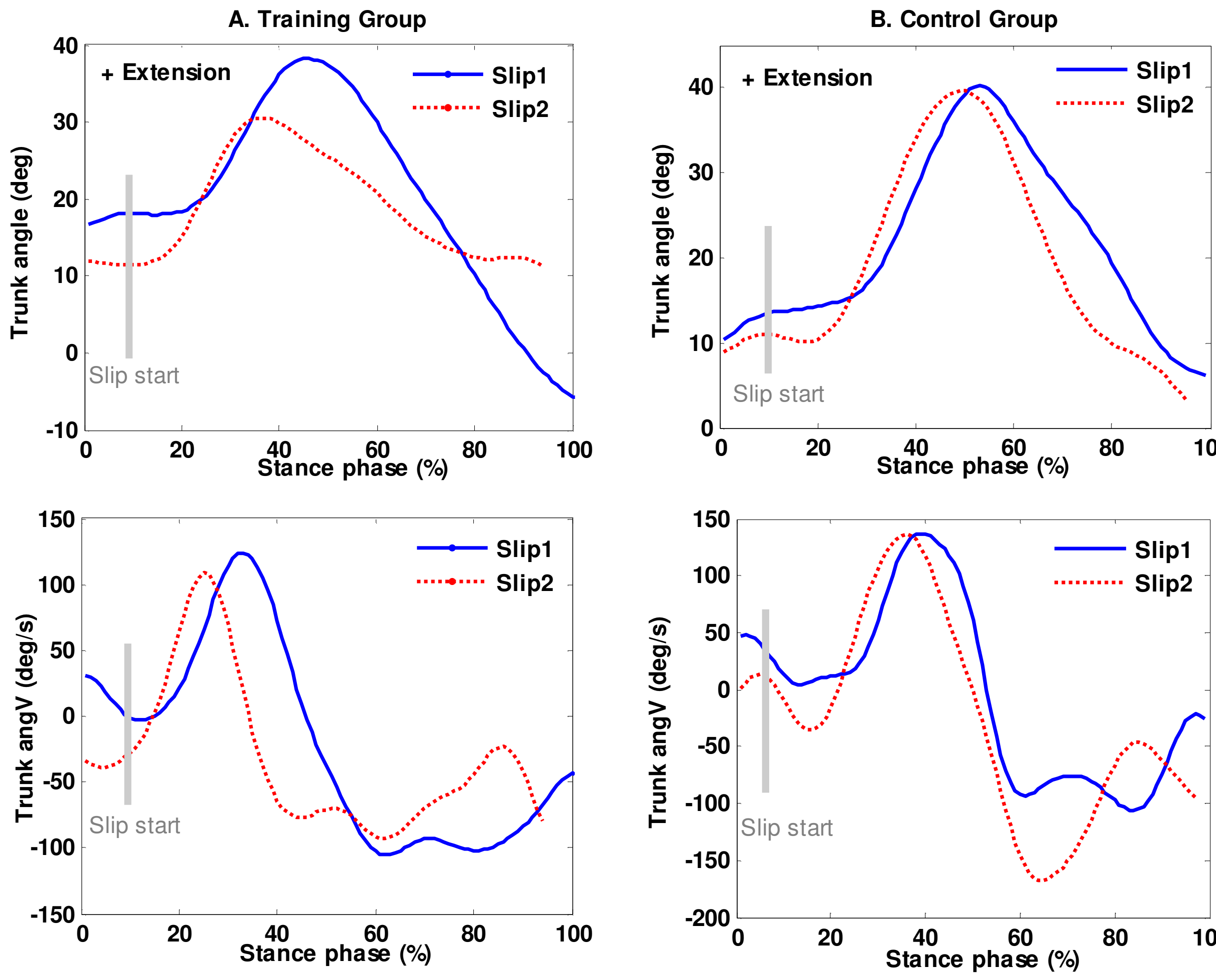

Figure 3.12 Ensemble averages of trunk angle and angular velocity during Slip1 and Slip2 trial between training and control group.

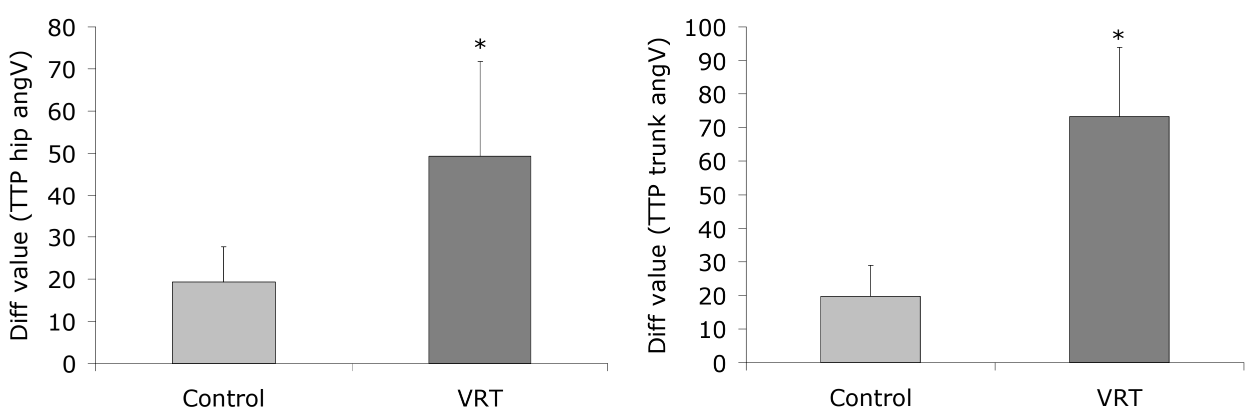

Figure 3.13 Difference values (Slip2 – Slip1) of time to peak (TTP) angular velocity (hip and trunk) between control and training group (*p < 0.05).

EMG measures

The ANOVA indicated an early onset of MH [$F_{(1, 18)} = 12.67, p = 0.01$] from Slip1 to Slip2 trial in the VRT group compared control. Early onset of VL muscles was also observed in the training group during Slip2, but the differences between the groups were not significant (Table 3.5). Along with early onset, the time to peak activation of the MH muscle decreased more from Slip1 to Slip2 [$F_{(1, 18)} = 11.55, p = 0.02$] in the VRT group compared to control. Peak knee coactivity decreased more from Slip1 to Slip2 in the VRT group compare to control [$F_{(1, 18)} = 21.34, p = 0.001$]. Peak ankle coactivity increased in the VRT group from the Slip1 to Slip2 trial, but the differences were not significant compared to control. The time to peak knee coactivity decreased more in the VRT group compared to control [$F_{(1, 18)} = 9.46, p = 0.01$] (Table 3.5).

Table 3.5 Mean ± SD of onset of muscle activity after slip-start and the time to peak activations (recovery trials only)

Variable	Group			
	Training		Control	
	Slip1	*Slip2*	*Slip1*	*Slip2*
Muscle activation onset (ms)				
Medial gastrocnemius	178 ± 35.67	180 ± 12.67	189 ± 24.29	179 ± 25.29
Tibialis anterior	187 ± 28.26	180 ± 11.69	188 ± 21.23	178 ±12.98
Medial hamstrings*	159 ± 14.76	138 ± 11.37	168 ± 15.28	156 ± 16.39
Vastus lateralis[†]	239 ± 33.54	222 ± 14.54	245 ± 25.76	255 ± 15.99
Time to peak activations (ms)				
Medial gastrocnemius	322 ± 15.50	310 ± 33.68	364 ± 15.39	377 ± 34.38
Tibialis anterior	325 ± 33.96	315 ± 28.45	378 ± 23.47	362 ± 32.53
Medial hamstrings*	280 ± 13.96	210 ± 17.45	290 ± 23.47	278 ± 22.53
Vastus Lateralis[†]	355 ± 25.35	345 ± 16.68	369 ± 33.12	354 ± 20.73
Coactivations				
Peak knee coactivity **	2.55 ± 1.19	1.57 ± 0.54	2.23 ± 1.39	2.44 ± 1.44
Peak ankle coactivity	1.68 ± 0.98	1.58 ± 0.45	1.95 ± 1.11	2.1 ± 0.99
Time to peak knee coactivity*	300 ± 33.16	260 ± 17.45	320 ± 44.47	310 ± 29.66
Time to peak ankle coactivity	295 ± 25.35	255 ± 36.68	319 ± 53.12	330 ± 20.55

Note. * $p < 0.05$, ** $p < 0.01$, [†]$p < 0.1$, p-value represent the statistics on the difference value (Slip2 – Slip1) between groups

Non-slipping foot measures

After evaluating the slipping foot timing characteristics (slip-start, slip-peak and slip-stop), the response time of the non-slipping foot was calculated and characterized as toe-off, foot-onset, foot-down and unperturbed foot reaction time. In general, the unperturbed foot reaction time decreased in the VRT group but the differences were not statistically significant. Similarly, no differences were found in the toe-off, foot-onset, and foot-down time of the non-slipping foot between the groups.

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. The COMvel at heel contact before slip-start increased significantly in the VRT group compared to control group [$F_{(1, 18)} = 9.76, p = 0.02$]. 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. However, participants in the VRT group had an increased trunk flexion at heel contact compared to control group [$F_{(1, 18)} = 3.46, p = 0.04$] during Slip2 trial. In terms of muscle activation, no significant effect of group was found in the onset of muscles at heel contact. No significant effect was found in the ankle and knee coactivity at heel contact between the 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-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-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. Although implicated, because of very few recovery trials per participant, it was difficult to generalize distinctive recovery strategies used. In addition, as participants were on the treadmill, there was an additional demand imposed on them to keep walking even during recovery attempts. This confounded recovery attempts in some participants. Thus, recovery trials where participants were able to continue walking after the slip perturbation were considered for interpretation. The SSQ score indicated minimal presence of cyber sickness after being in the VR for 25 minutes (a score of 20 or more indicates cyber sickness) (Table 3.6).

Table 3.6 Means ± SD of cyber sickness scores using the SSQ questionnaire reported from (n = 12) participants (maximum score of 40 indicates severe cyber sickness)

	Session (Mean ± SD)		
	Before VR	After VR training	Next day after VR training
SSQ Score	0	5.93 ± 2.46	0.66 ± 0.81

Due to few recovery trials per participant, it was difficult to generalize the reactive strategies. In terms of angular kinematics, the peak trunk extension angle decreased after the slip was initiated from T1-T3 trials. The lower extremity angular kinematics could not be generalized. In terms of neuromuscular response, a pattern of reduced peak ankle and knee coactivity was observed from T1-T3 trials (Fig 3.14).

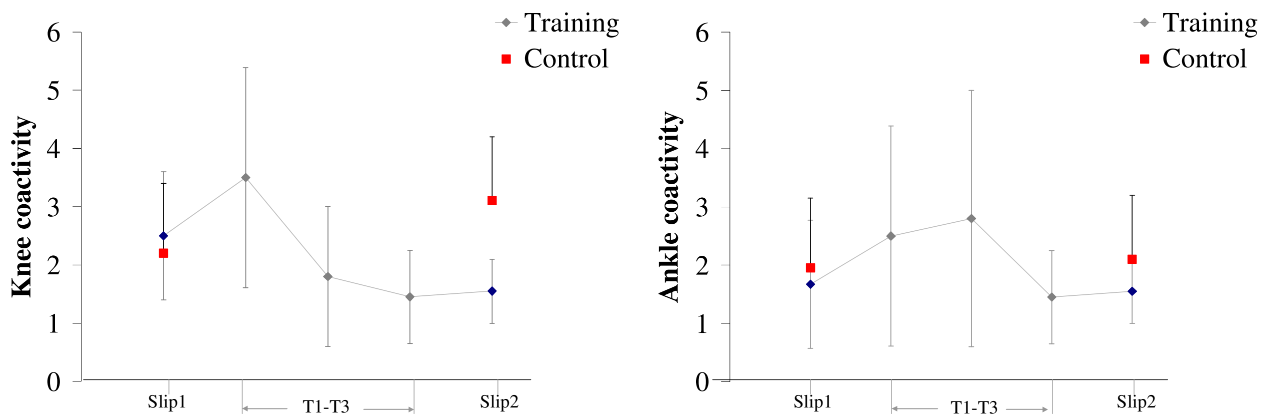

Figure 3.14 Mean ± 1 SD of peak ankle and knee coactivity from T1-T3 slip training trials (training group), and, from Slip1 and Slip2 trials (control and training group).

The proactive changes at heel contact were observed from T1-T12 trials. Participants walked with an increased trunk flexion, ankle plantarflexion (Fig 3.15), and knee flexion at heel contact from T1 to T2 trial, which reduced by T6 trial and remained unchanged from T6-T12 trials. In terms of muscle activity, participants had an early activation of all the muscles of the slipping limb at heel contact from T1- T2 trial, which remained unchanged until T5 trial. During the subsequent trials, early onset was only seen for VL and TA muscles.

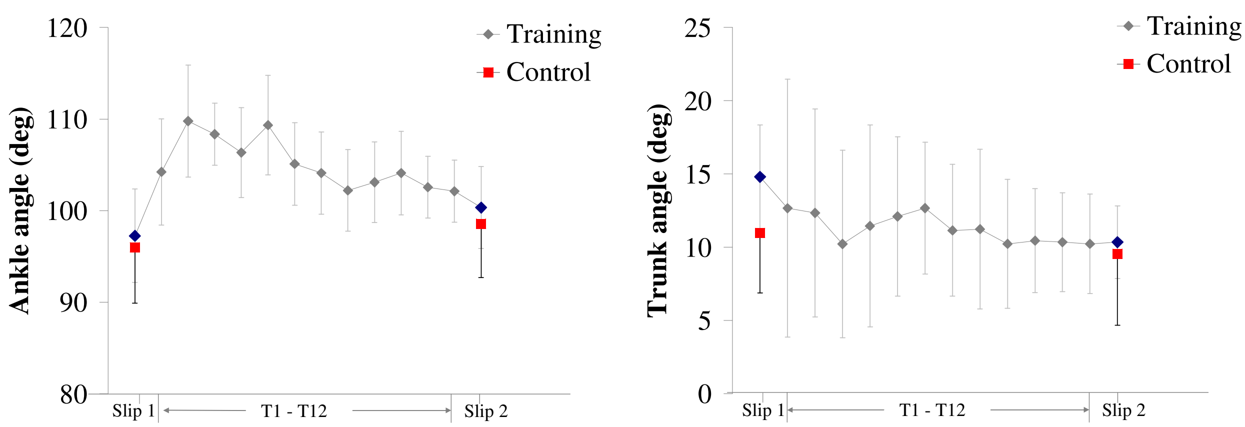

Figure 3.15 Mean ± 1 SD of ankle and trunk angles at heel contact from T1- T12 slip training trials (training group) and, from Slip1 and Slip2 trials (control and training group).

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 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 (Hollman et al., 2006), 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, stride velocity, and step width during the initial 5-10 min in the VR, which is similar to the findings by Hollman et al. 2006. 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. Similarly, the cautious gait behavior was observed in the angular kinematics and neuromuscular responses during the initial VR walking. Participants walked with an increased ankle plantarflexion, knee flexion and trunk flexion at the heel contact, which is similar to the findings in a previous study (Sheik-Nainar & Kaber, 2007). These kinematic changes were coupled with neuromuscular changes such as increased activation of MG and MH muscles during initial walking in the VR. After walking for 15 min in the VR environment, the kinematic and neuromuscular activations 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, specifically 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 lower that is 50% during Slip1 to 0% during Slip2. Although, fall frequency decreased in controls also during Slip2 (50% to 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 groups, 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 (Brady et al., 2000; Strandberg & Lanshammar et al., 1981; Perkins et al., 1978). Slips were initiated at similar time intervals for both 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.

In terms of angular kinematics, significant differences were only found in the trunk kinematics between the groups. During the Slip1 trial, both training and control group extended their trunk at ~ 130 deg/s before they were able to recover from the slip. However, during the Slip2 trial, participants in the training group extended their trunk at ~ 95 deg/s and were able to quickly reverse their forward trunk rotations by mid-slip. Reducing trunk rotations will have a significant effect in bringing the COM of the body within stability limits (Troy & Grabiner, 2006). Similar results were found during the VR training trials (T2-T3) where participants were able to reverse their forward trunk rotation after the visual perturbations were induced. Recovery patterns of the lower extremity joints were not evident during the VR training on treadmill. It took about 200-300 ms for the participants to react to a virtual slip. Therefore, after the slip was induced at right heel contact, the heel was traveling posterior to the non-slipping foot, and because of which the recovery consisted of a quick forward stepping response of the slipping foot, to avoid falling. However, due to limited data and large variability it is difficult to describe transfer of motor strategies from the training to Slip2 trial.

Several neuromuscular adaptations were also observed in the VRT group after the training. The onset and time to peak activation of the MH muscle of the slipping limb decreased in the VRT group during Slip2 compared to the controls. Slower hamstring activation rate in older adults has been suggested as a potential risk factor for slip-induced falls (Lockhart & Kim, 2005; Winter 1991). The initial muscular reaction to a slip consists of the activation of the hamstring muscle followed by other muscles (Chambers et al., 2007). This pattern is consistent with the kinematic response to a naturally occurring slip, i.e., primary knee flexion followed by knee extension. Early onset and the reduced time to peak MH activation therefore can help in stabilizing the knee joint during a slip. It may be possible that with training, older adults were able to improve the response time of the MH muscle compared to controls. Further reactive strategies include reduced knee coactivity of the slipping limb in the training group during Slip2 trial. Similar patterns were observed during the VR training, with an initial increase in the coactivity (T2 trial) and then a subsequent decrease (T2-T3). Although implicated, a generalized pattern could not be reported due to the lack of recovery trials. Coactivity was defined as a ratio of antagonist and agonist muscle activity of the ankle and knee. In general, the integrated EMG activity of both MH and VL increased from Slip1 to Slip2 in the training group, with a higher increase in integrated activity of MH after the slip was initiated. No significant differences were seen in the ankle coactivity, suggesting a reliance on knee stability for recovery. Coactivation of agonist and antagonist muscles is important for regulation of joint stiffness (Osternig et al., 1986; Simmons et al., 1988). It may be possible that after exposures to balance loss in the VR training, the CNS chose the most effective muscle synergy organization to achieve a common goal (i.e., recovery) with least energy expenditure during the Slip2 trial.

The results indicated presence of few proactive or feedforward strategies during training and transfer of training trials. Participants walked with an increased COMvel at heel contact during the Slip2 trial. Increases in the COMvel aids in maintaining balance when experienced with a slip (Lockhart et al., 2003; You et al., 2001; Pai et al., 1997). At the time of heel contact, the whole body COM is progressing forward and any change will alter the horizontal and vertical forces (Lockhart et al., 2003), affecting slip severity. Although the walking speed did not vary between Slip1 and Slip2, further analysis indicated an increased trunk angular velocity at the heel contact in the training group. Additionally, participants in the VR group had an increased trunk flexion at heel contact. Such movement strategy would allow participants to shift their COM anterior to the slipping foot even before the slip is initiated, hence reducing the correction necessary during reactive recovery (Pavol et al., 2002). No significant differences were found in angular kinematics of ankle, knee and hip of the slipping limb at the heel contact during Slip2 session indicating a natural gait behavior.

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 attributed to both proactive and reactive strategies employed by the training group. The main effects of training were observed in reducing the reaction time to recovery such as reduced time to peak knee coactivity, reduced slip distances, and reduced time to peak trunk extension. These effects may have reduced slip severity, leading to successful recoveries. Proactive strategies (increased COMvel and increased trunk flexion at heel contact) helped in improving the pre-slip stability.

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 (Nyberg et al., 2007; Keshner et al., 2004). Additionally, the study verified that healthy older adults were capable of walking in the VR environment with a stable gait after a period, which is contradictory to previous studies that found increased variability in the gait after VR walking (Hollman et al., 2007). 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 exist 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. It is also difficult to generalize the results outside the lab environment.

Future studies may explore different ways to induce visual tilts in the VR to make the perturbation novel to the participants each time. Additionally, the richness of the VR environment may be improved. It is important to test if similar VR adaptations can be seen in a larger cohort of older adults. Future research may examine the effects of VR intervention in improving balance in the fall prone elderly as they are at the highest risk of non-fatal and fatal injuries. Additionally, 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.

CHAPTER 4 – A COMPARISON OF MOVEABLE PLATFORM TRAINING AND VIRTUAL REALITY TRAINING IN REDUCING FALL FREQUENCY IN OLDER ADULTS

OBJECTIVE

Various exercise interventions are currently available that aim to improve balance and reduce fall accidents in older adults. Literature has produced mixed results in efficacy of these exercise interventions in reducing fall accidents (Mansfield et al., 2007; Kannus et al., 2005). The most effective type, intensity, and duration of training that can effectively reduce fall accidents is yet to be identified (Kannus et al., 2005). Recently, perturbation training has received a lot of attention for its use as a training tool to improve balance in older adults (Bhatt et al., 2006; Pai et al., 2003; Tjernstrom et al., 2002). The objective of this study was to compare the efficacy of two different training interventions (moveable platform and virtual reality) in reducing fall frequency and improving reactive recovery in older adults.

METHOD

Participants

Thirty-six healthy older adults (> 65 years, 18males and 18 females), were recruited for the study from the local community (Table 4.1). Written consent form approved by the Institutional Review Board (IRB) of Virginia Tech was obtained from the participants before participation. Exclusionary criteria included cardiovascular, respiratory, neurological, and musculoskeletal abnormalities as well as any other difficulties hindering normal gait (Appendix A). Additionally, a physician screened participants for lower extremity (ankle, knee, hip, heel, and toe) range of motion, and any balance related problems (i.e., Rhomberg, light touch test). Participants were equally divided into the control group, the moveable platform training group (MPT), and the virtual reality training group (VRT) using a stratified randomization that controls for age, gender, and body mass. All groups experienced two slip sessions (Slip1 and Slip2) on a (1:1) water and jelly-contaminated vinyl floor, separated by a repeated slip training session for the training groups, and a walking session for the control group.

Table 4.1 Participants demographics (control, moveable platform (MPT), and virtual reality (VRT) group)

	Group (Mean ± SD)		
	MPT (n = 12)	**VRT (n = 12)**	**Control (n = 12)**
Age (yrs)	71.24 ± 6.82	70.54 ± 6.63	74.18 ± 5.82
Mass (kg)	68.24 ± 8.04	67.77 ± 8.04	69.63 ± 9.45
Stature (cm)	167.45 ± 11.52	167.13 ±11.52	169.41 ± 9.16

Apparatus

The moveable platform training was conducted by inducing slips using a custom built sliding device consisting of a low friction, motorized moveable platform (40x120cm). Slips were induced by a computer-controlled program that moves the platform after the heel contact of the slipping foot, when the vertical ground reaction force of the trailing limb drops below a threshold (i.e., 40% of body weight was lifted off the force plate). Details of this set-up are provided in chapter 2 (method section). The virtual reality training was conducted by inducing visual perturbation while participants walked on a treadmill. A virtual reality scene (i.e., regular downtown area) was rendered on a head mounted display (HMD). The virtual slip consisted of perturbations (tilts) in the pitch plane in the VR scene at random intervals. Details of this set-up are provided in chapter 3 (method section).

All groups performed slip trials on a slippery floor surface twice (Slip1 and Slip2), separated by a training session for the training groups, or a normal walking session for the control group. The slip trials were conducted on a walkway 15 m long. The walkway was embedded with two force plates, which was used to record gait characteristics and induce an actual slip. The slippery surface (i.e., top of one the force plates) was covered with a water and jelly mixture (1:1) to reduce the coefficient of friction (COF) (dynamic COF = 0.12) of the floor surface. Unexpected slips were induced while participants walked on the walkway. Details of this set-up are provided in chapter 2 (method section)

Measurement

Full-body kinematics were recorded at 100 Hz using a six-camera motion capture system (Qualisys). Twenty- four reflective markers were attached to various bony landmarks of the body. The marker configuration was similar to previous studies (Lockhart et al., 2003). Kinetic data were collected at 1000 Hz from the force plates. Eight-channel EMG telemetry Myosystem 2000 (Noraxon, USA), was used to record bilateral temporal activations of various muscles in the lower extremity during all the sessions. Bipolar Ag-AgCl surface electrodes was placed over vastus lateralis (VL), medial hamstring (MH), and tibialis anterior (TA) and medial gastrocnemius (MG) muscles of the lower extremity. The EMG data were sampled at 1000Hz. A LabVIEW program synchronized the data collection from the motion capture system, force plates, and EMG system. Uniform clothes and shoes were provided to all participants to minimize loose clothing and shoe-sole differences. Participants wore a full body fall-arresting harness throughout the experiment (Lockhart et al., 2003).

Protocol

The experiments were divided into three sessions: baseline measure, training acquisition, and transfer training, on three separate days. During the first session, all participants underwent a slip trial on a slippery floor surface as a baseline measure. After two weeks, the training groups performed the slip training and the control group performed normal walking trials. During the third session, all groups were exposed to a slippery floor surface similar to the baseline session.

All participants underwent a slip trial on a slippery floor surface to get a baseline measure before they proceeded to the training session. Details on the baseline session and transfer of training session are provided is chapter 2 (method section).

The MPT group went through repeated simulated slips induced by moving a platform while the participants stepped on it. Participants were unaware of the position of the moveable platform. After collecting data from the walking trials, a simulated slip was induced by moving the platform 0.3 m at a speed of 1.2 m/s (acceleration at 20 m/s^2). The training session consisted of 24 trials of slips and no slips (blocked and randomized) (Fig 4.1). Whole body kinematics, kinetic and EMG data were recorded during all the trials. Details of this protocol are provided in chapter 2 (method section).

T1-T3	N1-N3	T4-T6	N4-N6	R1……………………………………R12
Slip	No slip	Slip	No slip	Random variations of slip (T7-T12) and no slip (N7-N12)

Figure 4.1 Experimental protocol for the repeated slip paradigm, consisting of 24 trials of blocked slip and no slip trials (12) and randomized slip and no slip trials (12)

The VRT group performed the training on a treadmill while wearing a HMD with a virtual scene displayed. Participants wore a head mounted display, and the moving scene was adjusted to their speed of walking on the treadmill. After being habituated to the VR, participants were told to look straight ahead and that a slip may or may not be induced. A sudden virtual slip was induced by tilting the environment 25 degrees in the pitch plane at 60º/s. The training consisted of 24 trials of slips and no virtual slips (blocked and randomized) (Fig 4.1). Whole body kinematics, kinetic and EMG data were recorded during all the trials. Details of this protocol are provided in chapter 3 (method section).

After the training groups performed training trials, and the control group performed normal walking trial, all groups came back for the transfer for training session on a slippery surface. The experimental protocol was similar to the baseline slip, and served as Slip2.

Data Analyses

The converted co-ordinate kinematic (marker data) and kinetic (force plate) data were low-pass filtered using a fourth order, zero lag, Butterworth filter at a cut off frequency of 7 Hz. The EMG data were digitally band pass filtered at 10-450 Hz following data collection (Chambers et al., 2007), following which they were rectified and low-pass filtered using a fourth order, zero lag Butterworth filter with a 7 Hz cut off frequency to create a linear envelope (Tang et al., 1998; Chambers et al., 2007). All kinematic analyses were performed in the sagittal plane. For normal walking and slip recovery trials, the analyses were conducted for the stance phase (heel contact to toe off).

Dependent variables

The dependent variables consisted of several slip severity measures, muscle activations, and angular kinematics during Slip1 and Slip2 trials.

1) Slip distances (SDI & SDII) and peak sliding heel velocity was used to describe the severity of slip. Details provided in chapter 2 (method section).

2) EMG activation onset and time to peak activation was calculated for all muscles (chapter 2, method section).

4) Knee and ankle coactivity (ratio of antagonist and agonist muscle pairs), and the time to peak coactivity was calculated (chapter 2, methods section).

3) Angular kinematics included peak ankle flexion, knee flexion, hip flexion, and trunk extension angles after slip-start, along with angular velocities (chapter 2, method section)

4) Unperturbed foot reaction time was calculated as the difference between the foot onset and foot down of the unperturbed foot after the slip-start (chapter 2, methods section).

To examine any training induced proactive changes in participants several gait measures were included: 1) center-of-mass velocity at heel contact, 2) transitional acceleration of the whole body center- of-mass, 3) ankle, knee, hip, and trunk angles at heel contact, 4) muscle onset and coactivity (ankle and knee) at heel contact. Details on these parameters are provided in chapter 2 (method section).

To examine effects of the two different training interventions (MPT, VRT) on reducing slip severity and improving recovery reactions, difference values were calculated between the two slips (Slip2 – Slip1), and a one-way analysis of variance (ANOVA), was conducted on each dependent measure between the two groups. The frequency of falls was analyzed between the two groups (control vs. training) for Slip1 and within the training group (Pre and Post) using the chi square (χ^2) test statistic. To determine if both groups had similar gait and slipping characteristics during Slip1, a one-way ANOVA was conducted on gait measures (COMvel, TA, and RCOF at heel contact), and slip measures (SDI, SDII and PSHV). All statistical analyses were conducted using SPSS 11.5.0 (Chicago, IL) with a significance level of $p \leq 0.05$ for all tests. In order to verify the assumptions of ANOVA, all of the data were evaluated for normality (using Shapiro-Wilk W test), and sphericity (using Bartlett's sphericity test). The results indicated no significant violations of assumptions.

RESULTS

The fall frequency reduced significantly in the MPT (*p = 0.001*) and VRT (*p = 0.003*) compared to control group (Table 4.2). All groups were at a similar fall rate during the first unexpected slip, accounting for no group differences. Table 4.3 and 4.4 summarizes the various dependent variables related to proactive and reactive adaptations that were influenced by MPT and VRT.

Table 4.2 Frequency of falls before and after the training interventions

	MPT (n = 12)		VRT (n = 12)		Control (n = 12)	
	Slip1	Slip2	Slip1	Slip2	Slip1	Slip2
Frequency of falls (%)	41% (5)	0% (0)	50% (6)	0% (0)	50% (6)	25% (2)

Table 4.3 Statistical differences in proactive adjustments when compared between moveable platform training (MPT), virtual reality training (VRT), and control.

Dependent Variables	Group MPT vs. C	Group VRT vs. C	Group MPT vs. VRT	Dependent Variables	Group MPT vs. C	Group VRT vs. C	Group MPT vs. VRT
Kinematics				**EMG**			
angles at heel contact				*Activation Onset*			
Ankle plantarflexion	-	-	-	MG (ankle plantflex)	-	-	-
Knee flexion	+	-	-	TA (ankle dorsiflex)	-	-	-
Hip flexion	-	-	-	MH (knee flex)	*	*	-
Trunk flexion	-	*	†	VL (knee ext)	-	-	-
Gait				*Coactivity*			
COM velocity	**	*	-	Knee	-	+	-
transitional acceleration of COM	**	+	*	Ankle	-	-	-
friction demand (RCOF)	-	-	-				

Note. * $p < 0.05$, ** $p < 0.01$, † $p < 0.1$, -- no significance, p-value indicates the statistics performed on difference values (Slip2 – Slip1) between groups.

Table 4.4 Statistical differences in reactive recovery parameters between moveable platform training (MPT), virtual reality training (VRT), and control (MG- medial gastrocnemius, TA- tibialis anterior, MH- medial hamstring, VL- vastus lateralis)

	Group		
Dependent Variables	**MPT vs. C**	**VRT vs. C**	**MPT vs. VRT**
Slip measures			
Slip distances and heel velocity			
SDI	*	*	-
SDII	**	*	-
PSHV	**	*	†
EMG			
Activation Onset			
MG (ankle plantflex)	†	-	-
TA (ankle dorsiflex)	*	-	†
MH (knee flex)	*	*	-
VL (knee ext)	-	†	-
Time to peak activation			
MG (ankle plantflex)	†	-	-
TA (ankle dorsiflex)	**	-	*
MH (knee flex)	**	*	-
VL (knee ext)	†	†	-
Peak Coactivity			
Knee	**	**	-
Ankle	*	-	*
Time to peak coactivity			
Knee	*	**	-
Ankle	†	-	-

	Group		
Dependent Variables	**MPT vs. C**	**VRT vs. C**	**MPT vs. VRT**
Kinematics			
Peak angles			
Ankle plantarflex	-	-	-
Knee flex	**	-	†
Hip flex	*	-	-
Trunk ext	-	*	†
Time to peak angles			
Ankle plantarflex	-	-	-
Knee flex	-	-	-
Hip flex	*	-	-
Trunk ext	-	†	-
Peak angular velocity			
Ankle plantarflex	-	-	-
Knee flex	*	-	*
Hip flex	†	†	-
Trunk ext	†	*	*
Time to peak angular velocity			
Ankle plantarflex	-	-	-
Knee flex	-	-	-
Hip flex	*	*	-
Trunk ext	*	*	-
Unpert. Foot reaction time	*	-	-

Note. * $p < 0.05$, ** $p < 0.01$, † $p < 0.1$, - no significance, p-value indicates the statistics performed on difference values (Slip2 – Slip1) between groups

In terms of proactive adjustments, significant differences were found in TA (p = 0.04) between MPT and VRT groups. TA reduced more from Slip1 to Slip2 in the MPT group compared to the VRT group. No significant differences were observed in other proactive adjustments between MPT and VRT groups. In terms of reactive recovery, the one-way ANOVA between MPT and VRT group indicated significant differences in the peak trunk angular velocity (p = 0.01) and peak knee angular velocity (p = 0.001). The peak knee angular velocity decreased more from Slip1 to Slip2 in the MPT group compared to the VRT group (Fig 4.2). The peak trunk angular velocity reduced more in the VRT group compared to the MPT group (Fig 4.2). No significant changes were found in the other peak angles and angular velocities.

Significant differences were found in the time to peak angle and angular velocities between the groups. The peak ankle coactivity reduced more in the MPT group (p = 0.001) compared to the VRT group (Fig 4.3). The knee coactivity decreased in both MPT and VRT group but no significant differences were found (Fig 4.3). No significant differences were found in the onset of muscle activity (MG, TA, MH, and VL) between groups. However, time to peak TA muscle activity decreased more in the MPT group compared to the VRT group (p = 0.02). In terms of slip severity, both training groups reduced slip distances and peak sliding heel velocity, however no significant differences were observed between them.

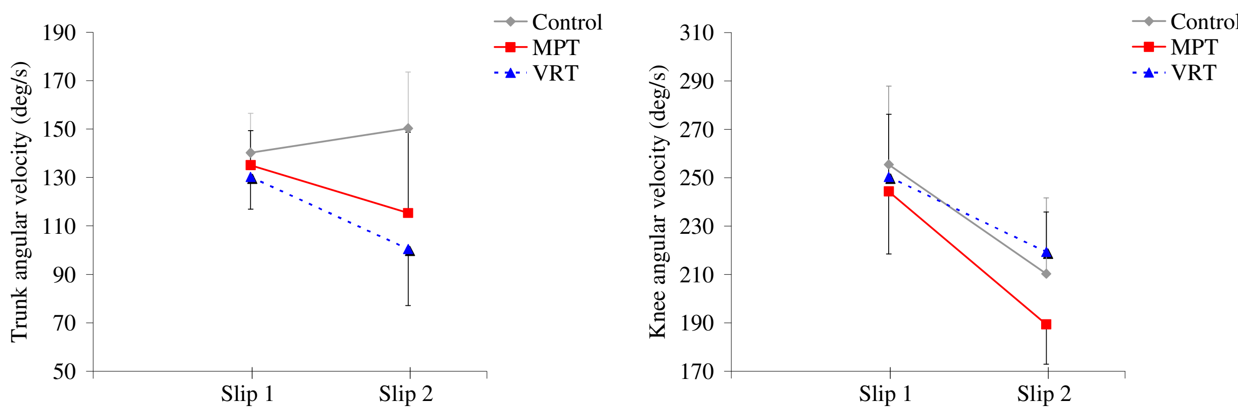

Figure 4.2 Mean ± 1 SD of peak trunk and knee angular velocity between control, moveable platform (MPT), and virtual reality (VRT) training groups while recovering from a slip

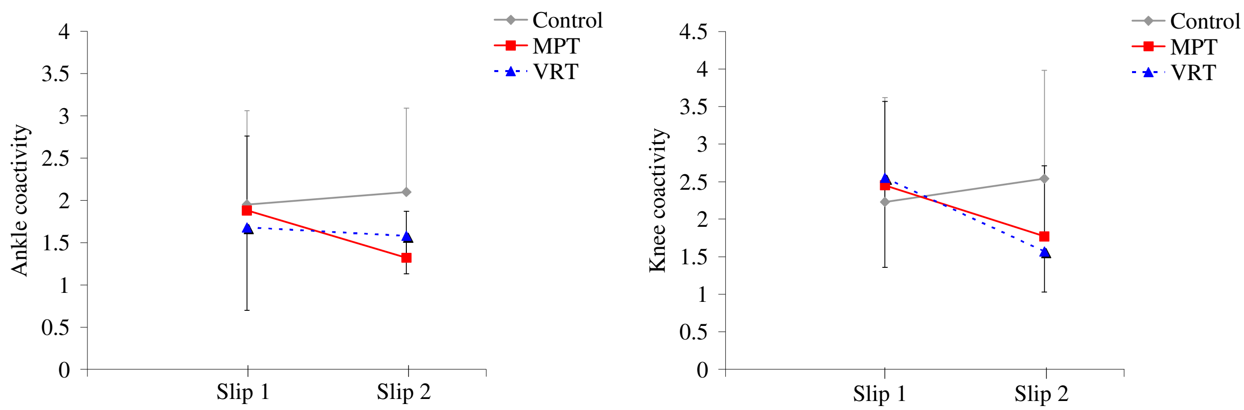

Figure 4.3 Mean ± 1 SD of peak ankle and knee coactivity between control, moveable platform (MPT), and virtual reality (VRT) training groups while recovering from a slip

DISCUSSION

The objective of the study was to compare efficacy of two different perturbation training (MPT and VRT) methods in reducing fall frequency and improving recovery mechanisms in older adults. Both training groups were able to reduce their fall frequency after training (MPT: 41% to 0%, VRT: 50% to 0%). Both training methods were able to reduce fall frequency via proactive and reactive adjustments after the training.

The comparison indicated a significant effect of VRT in reducing forward trunk rotations as compared to the MPT group. As discussed in chapter 3, reducing trunk rotations will have a significant effect in bringing the COM of the body within boundaries of stability (Troy & Grabiner, 2006). The VRT group had a significant effect on lower extremity angles and angular velocity; with a decreased peak knee flexion angle and angular velocity compared to the VRT group. Similar adaptations were observed in the MPT group during training, indicating a positive transfer may have occurred. In terms of proactive changes, MPT group had a significantly reduced TA. TA is important in assessing the forward momentum of the body during recovery from a backward loss of balance (Lockhart et al., 2003). Both training methods had an effect on the neuromuscular characteristics (reduced knee coactivity, early activations of the muscles).

However, ankle coactivity significantly reduced in the MPT group as compared to the VRT group.

In general, significant changes were observed in the lower extremity corrections to a slip in the MPT group, as compared to the upper body (i.e., trunk) corrections in the VRT group. This may be expected due to the differences in the perturbations used by each training method. The moveable platform created a whole body perturbation by moving the foot over it. Due to this, participants may have initiated recovery reactions using their lower extremity (ankle and knee), and a secondary response by using their hip and trunk. In the VRT training, the visual perturbation induced an initial perturbation to the upper body (head, neck, arms, and trunk), followed by a secondary response by using the lower extremity. Similar results were reported by Bugnariu et al. (2007), where older participants initiated balance reaction by activating their neck muscles first in response to a VR-induced sensory conflict while standing still, suggesting an excessive reliance on visual inputs. In this study, during the VRT training, participants did not experience more than 2-3 perturbations and thus it was difficult to generalize the changes to Slip2. Whereas in the MPT group, older participants modulated their proactive and reactive strategies during training, and reached a stable plateau by 6-7 training trials. This may be used as preliminary information on the time older adults required to refine and adapt their movements when experienced with slip perturbation.

In terms of feasibility, both training methods had their advantages and limitations. One of the limitations of the VRT study was the inability to induce perturbations in older adults after 2-3 training trials. Participants adapted their walking to the VR and the visual perturbation. However, it required less space utilization (i.e., treadmill and the HMD), and has a potential to be used as a mobility tool for older adults with gait instability based on the results from chapter 3. Due to its portability, it may be beneficial to be used in community and care facilities. Additionally, older participants in the study were comfortable wearing the HMD and provided positive feedback on the VR environment experience. A few studies have shown a beneficial effect of VR in improving mobility in older adults (Fung et al., 2007; Bugnariu et al., 2008). VR environments can be easily altered to create a desired scene, with perturbations in any direction. By using different intensities and types of visual tilts of the VR scene, VR environment can be made more rich and novel to the participants.

In the MPT training, the moveable platform was able to induce perturbation in participants in all the training trials. After the initial training trials, even if participants made significant proactive changes while approaching the platform, a slip was induced in them by moving the platform. Therefore, repeatability was an advantage in the MPT training. However, more space is required to create the whole set-up and significant cost may be involved (i.e., force plate, motorized unit, and track). Additionally, two participants reported anxiety while approaching the moveable platform due to the physical perturbation. Further studies may evaluate the dose-response relationship between different speeds, distance of movement, and biomechanical and neuromuscular changes.

In summary, both training interventions have a potential to be used as slip-training methods for older adults. Future studies may test these interventions with a larger population sample, especially the fall prone individuals who are at the highest risk for injury. Additionally, future studies may evaluate the retention of the training effects. Furthermore, it would be beneficial to conduct a longitudinal study to report fall frequency in the participants post training.

CHAPTER 5 – SUMMARY AND CONCLUSIONS

SUMMARY

Slip-induced fall accidents are associated with significant injuries and medical costs in older adults. Identifying fall protection and prevention strategies to reduce fall accidents in older adults has been a goal of researchers in the past few decades. Existing fall prevention 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 (Mansfield et al., 2007; Kannus et al., 2005).

Preliminary studies on motor learning based training programs specifically for fall prevention have yielded hopeful results (Bhatt et al., 2006; Pavol et al., 2002). In general, an increased ability to recover from a fall upon repeated exposure to simulated slip perturbation was observed in younger adults. The improvements were attributed to the adaptive refinement of the CNS via feedforward and feedback mechanisms. These studies however have been limited by the lack of adequate information about the transfer of the motor skills learned on an actual slippery surface (i.e., generalizability). Pavol et al. (2002) reported that older adults were capable of learning to recover when perturbed from a sit-to-stand task. Although implicated, no studies to date have examined the efficacy of repeated perturbation training in reducing fall frequency in older adults. First, there is a need to investigate if older adults can learn motor skills specific to slip-recovery using a repeated perturbation training paradigm and transfer the learned strategies to an actual slip. Second, there is a need to evaluate various biomechanical and neuromuscular changes, which may alter with the training.

The aim of this study was to examine the efficacy of two different perturbation training interventions using moveable platform and virtual reality environment in improving recovery mechanisms and reducing fall frequency in older adults. Older adults were divided into three groups (moveable platform training (MPT), virtual reality training (VRT), and control). All groups underwent two slip trials (Slip1 and Slip2) on an actual slippery surface on different days, separated by training for the training groups, and normal walking for the control group.

Both MPT and VRT groups were able to reduce fall frequency after the training. The study used a pretest-posttest design to find differences in all groups between Slip1 and Slip2, to quantify effects of training. The results were divided into three separate categories: 1) evaluating performance of participants before slip onset during heel contact (proactive strategies), 2) evaluating performance of participants after slip onset during recovery (reactive strategies), and 3) investigating the various learning strategies during the training session. In general, both MPT and VRT groups were able to improve recovery strategies during training and transfer them to a slippery surface as compared to the control group.

The MPT group was able to learn recovery strategies during the training, and a learning plateau of the performance measures (peak angles, peak angular velocity, onset of muscle activations, peak ankle and knee coactivity) were seen within 6-7 training trials. Some of these measures were retained in the post-training slip session on an actual slippery surface, indicating positive transfer (refer to chapter 2). Significant proactive (increased COMvel, TA), and reactive (reduced time to peak activations and coactivity (ankle and knee), reduced time to peak angles (knee and hip) and angular velocity (hip and trunk), and reduced slip displacement) adjustments were observed in the MPT group as compared to the control group (refer to chapter 2). The major contribution of this study was the evidence of motor learning in older adults (> 65 years) and their ability to transfer learned strategies in the transfer of training session.

The VRT group was able to reduce fall frequency after the training as compared to the control group. There were significant proactive (increased COMvel, increased trunk flexion at heel contact), and reactive (reduced time to knee coactivity, reduced time to peak trunk angle and trunk angular velocity, and reduced slip displacement) adjustments as compared to the control group in the transfer of training session. However, during the virtual reality training, a ceiling effect was observed, as participants did not react to any virtual slips after 2-3 training trials. This limited the ability to describe distinctive strategies utilized by participants during recovery since learning curves could not be obtained for all performance measures. The study however found that the older adults habituated to the VR environment while walking on the treadmill, and reduced their gait variability after 15 - 20 min. The major contribution of this study is the evidence that VR environments may be used to induce perturbations in older adults similar to a slip. Additionally, older adults were able to improve recovery reactions and reduce fall frequency in the transfer of training session.

FUTURE RECOMMENDATIONS

While outcomes from this study have contributed to the understanding of various biomechanical and neuromuscular adaptations induced by perturbation training methods in older adults, there are areas that still need further investigation. The moveable platform training in the current study used a fixed distance of movement of the motorized platform. Future studies may explore the dose-response relationship by changing the dose (distance and speed of the motorized platform), and examining the changes in the performance measures (reactive recovery). Similarly, the virtual reality training may be improved by utilizing visual tilts in different planes other than pitch plane to make the perturbations novel to the participants each time. Additionally, based on the results from the VR study, VR environments may have a potential in improving gait stability in older adults. Future studies may examine effects of walking in a VR environment for longer durations in older adults with mobility problems.

In general, there is a need to test the efficacy of the suggested training interventions with a larger cohort of older population, specifically fall prone older adults. Findings from the current study contributed to the knowledge of various biomechanical and neuromuscular parameters that were sensitive to training (i.e., trainability of some mechanisms). This information may be used as a preliminary data to improve the existing perturbation training methods to further refine the recovery reactions in older adults. In this study, retention of training benefits was seen the next day in the transfer of training session (1 day). There is a need to understand the relationship between intensity and duration of training to its retention. It is important to determine if the level of performance achieved during training is short term or long term. Finally, although beneficial effects of training were observed in this study, it was a controlled lab experiment and the effects of the proposed training methods need to be investigated outside the laboratory. For example, if the training has to be recreated in a community center, it has to be designed based on the characteristics of the users such as their age, strength capabilities, history of visual or vestibular deficit, fear of falls, and so on. Based on these factors, the intensity, duration, type of perturbation (i.e., whether VR or MP) of the training will need be altered.

CONCLUSIONS

Overall, the current research has expanded our knowledge on the use of repeated perturbation training in improving recovery reactions in older adults. The goal of this study was to examine the efficacy of perturbation-based training using existing tools (moveable platform) and using new tools (VR) in reducing slip-induced fall frequency specifically in older adults. The moveable platform training study was one of the first known studies that provided a detailed description of various biomechanical and neuromuscular adaptations via which older participants were able to learn and transfer motor strategies. This information has an important implication in the future research on training and improving motor learning in older adults. One of the major findings from this study is that healthy older participants were capable of learning specific motor skills during training on the platform and transfer them to a different situation (i.e., an actual slip). With this knowledge, the next step is to test if this training can be recreated in a community and care center to help improve balance in elderly.

The use of VR as a slip training method has only been suggested prior to this study. The virtual reality training study provided preliminary empirical evidence on the use of VR as a perturbation-based training tool. The time required by the older adults to walk with a natural gait once immersed in VR is one of the major findings of the study and has implications in the future VR setups for locomotion research. Decreases in the gait variability after walking in the VR for a prolonged time may be utilized in gait training of older adults with mobility problems. It is important realize that the efficacy of VR training can only be validated after testing it with a larger cohort. The portability of the VR set-up may have an advantage to be used in medical facilities and community care centers to provide gait training to older adults. In conclusion, both training interventions were able to reduce fall frequency in older adults within a laboratory environment.

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APPENDIX A – MEDICAL HISTORY FORM

MEDICAL HISTORY AND EMERGENCY CONTACT FORM

Study Title: Effects of perturbation training methods on reducing slip-induced falls in older adults

IRB #:

Date: ________________ Participant Code Number (ID): ___________________

Gender: [ ] Male [ ] Female Age: _____ Height (ft/in): ________ Weight (lb): ______

Other Study Specific Measurement(s): ____

IN CASE OF EMERGENCY CONTACT: Name: ________________________ Phone: _____________

GENERAL INFORMATION

Do you experience:

Shortness of breath	[ ] NO	[ ] YES
Dizziness	[ ] NO	[ ] YES
Headache	[ ] NO	[ ] YES
Easily fatigued	[ ] NO	[ ] YES
Pain in arm, shoulder or chest	[ ] NO	[ ] YES

If Yes was checked, please explain:

Are you currently taking prescription or other medication? If so, please list (e.g., for arthritis, pain, bone loss, high blood pressure, immunosuppression, calcium supplements or Fosamax):

Have you experienced any slips or falls, and if so, how long ago? Please explain:

BONE AND JOINTS		
Have you been diagnosed with osteoporosis (thinning of the bones)?	[ ] NO	[ ] YES
Have you experienced fractures of one or more bones in the past 3 years?	[ ] NO	[ ] YES
Have you had a DEXA scan (bone scan) done in the past 4 years?	[ ] NO	[ ] YES
Have you had hip or knee replacement surgery, or ankle surgery?	[ ] NO	[ ] YES
Do you have arthritis in your hands, knees, ankles, etc.?	[ ] NO	[ ] YES
Do you have routine back or neck pain?	[ ] NO	[ ] YES
Have you had surgery on your spine (back) or neck to relieve pain?	[ ] NO	[ ] YES
Have you had knee ligament problems?	[ ] NO	[ ] YES
If you had knee problems, was surgery required for treatment?	[ ] NO	[ ] YES
Do you have a fallen arch (flat foot) in either of your feet?	[ ] NO	[ ] YES

Have you had long-term shoulder pain or surgery on your shoulder?	[ ] NO	[ ] YES
BRAIN AND NERVOUS SYSTEM		
Have you ever had a stroke?	[ ] NO	[ ] YES
If you have had a stroke, has it left you with weakness in an arm or leg?	[ ] NO	[ ] YES
Do you have Parkinson's disease?	[ ] NO	[ ] YES
If you have Parkinson's disease, does it affect your balance or walking?	[ ] NO	[ ] YES
Do you have any inner ear problems causing dizziness or affecting your balance?	[ ] NO	[ ] YES
Do you have pinched nerves in your spine affecting walking or sensation in your legs?	[ ] NO	[ ] YES
Are you currently taking any medicines that cause you to be dizzy?	[ ] NO	[ ] YES
Have you ever had a detached retina in your eye?	[ ] NO	[ ] YES
MUSCLES		
Do you frequently experience muscle weakness?	[ ] NO	[ ] YES
Have you been diagnosed with any muscle wasting disease?	[ ] NO	[ ] YES
Have you ever had an inguinal or other hernia?	[ ] NO	[ ] YES
If you have had a hernia, was it surgically repaired?	[ ] NO	[ ] YES
Do you require a cane or a walker to facilitate your walking?	[ ] NO	[ ] YES
HEART AND CIRCULATORY SYSTEM		
Do you tire easily or get out of breath quickly when walking?	[ ] NO	[ ] YES
Have you had a heart attack?	[ ] NO	[ ] YES
Do you have an enlarged heart or congestive heart failure?	[ ] NO	[ ] YES
Do you have an uncorrected or surgically corrected aortic aneurysm?	[ ] NO	[ ] YES
Do you have diabetes?	[ ] NO	[ ] YES
If you have diabetes, have you been told that you have diabetic neuropathy in your feet (affecting sensation or circulation in your feet)?	[ ] NO	[ ] YES
Do you have hemophilia (inability of your blood to clot)?	[ ] NO	[ ] YES
Are you taking medicines to thin your blood (e.g., coumadin, heparin)?	[ ] NO	[ ] YES
SKIN		
Are you allergic to tape, adhesives, or gels used to attach electrodes to your skin?	[ ] NO	[ ] YES
Have you had any allergic reactions to skin creams or disinfectant solutions applied to the skin (e.g., alcohol, iodine)?	[ ] NO	[ ] YES

APPENDIX B – SIMULATOR SICKNESS QUESTIONNAIRE

	Rating				
SSQ Symptom	***0***	***1***	***2***	***3***	***4***
General discomfort					
Fatigue					
Headache					
Eyestrain					
Sweating					
Nausea					
Fullness of head					
Blurred vision					
Dizzy (open eyes)					
Dizzy (close eyes)					
Total score					

Note. 0-none, 1- slight, 2-Moderate, 3-severe, 4-unbearable

APPENDIX C – SNELLEN'S CHART

Top line indicates 20/20 visual acuity

APPENDIX D – CONSENT FORM

CONSENT DOCUMENT FOR PARTICIPANTS IN
RESEARCH PROECTS INVOLVING HUMAN SUBECTS

Locomotion Research Laboratory
Virginia Polytechnic Institute and State University

TITLE OF PROECT: Effects of perturbation training methods on reducing slip-induced falls in older adults

PRINCIPAL INVESTIGATOR: Thurmon E. Lockhart Ph.D., Grado Department of Industrial and Systems Engineering, Virginia Tech

I. Purpose of this Research Project

Older adults are at a higher risk of falls due to the way they walk and problems with their posture. They face a greater risk when walking on slippery surfaces. More than 25% of older adults fall every year, with emergency departments treating more than 1.6 million seniors due to fall-related injuries annually, resulting in the hospitalization of 373,000. Due to increases in life expectancy in the past century, the size of older population (above 65 years) is growing and is expected to reach 54.6 million by 2020 (U.S. Census Bureau, 2006). Because the prevalence of fall injuries is high among older adults, there is a need for prevention strategies that may help reduce the risks associated with falls. Several exercise programs have been suggested to improve balance in the elderly, but their success in preventing falls post training is not well documented. A training intervention may be effective in reducing falls, if it can help older adults to practice movements related to recovering from a fall.

The aim of the current study is to develop training methods to reduce fall incidence in older adults. The training will be designed to help participants practice movements related to recovering from a fall. The idea here is to induce a balance loss similar to that of slipping. By providing a repetitive exposure to such a balance loss in a controlled manner, participants may learn movements necessary to prevent a fall. The study will evaluate the effectiveness of two different training methods- one using a moveable platform, and the other using a treadmill along with a visual display. The moveable platform training will utilize a motorized platform which will move as participants step on it, inducing a balance loss similar to slip. By repetitive practice on such a platform, participants may learn movements required to prevent a fall. The treadmill and the visual display training will utilize a virtual display of a regular street. Here, participants will walk on the treadmill wearing a visual display. The visual display will move in the same speed as that of the treadmill. At random instants, there will be a sudden movement of the display, which may induce a balance loss similar to slip. By repetitive practice of walking on the treadmill after the balance loss, older adults may learn movements required to prevent a fall.

The effectiveness of these training programs will be tested by recording motion data (using reflective markers) and muscle activity (using electrodes) before, during, and after the training intervention. The new training programs are expected to improve balance reactions specific to slip-induced falls in older adults. If the training program is effective, it may be easily incorporated in the nursing home facility, or hospitals to improve balance in fall prone elderly.

II. Procedures and Project Information

A. Participant Selection

Solicitation and Selection of Study Participants - A total of seventy two (72) young adult (18-30 yrs) and elderly individuals (65-85yrs) will be enrolled and participate in this study.
Inclusion Criteria – To be considered for this study, you must be an adult, in the 18-35 or 65-85 year age groups, with none of the exclusionary criteria listed below.
'Exclusion Criteria', 'or any other diseases or medical conditions that would make participation unsafe' – Individuals with a history of, or signs and symptoms of cardiovascular, neurological, or bone and joint problems should not participate in this study. The study physician must approve subjects' participation.

- Cardiovascular problems: e.g. chronic heart failure; enlarged heart (cardiomyopathy), bulging of the aorta, weakened heart; pain in the feet due to chronic diabetes; disorder of blood clotting system (hemophilia).
- Respiratory problems: e.g. getting tired easily or difficulty in breathing upon normal walking.
- Neurological problems: e.g. stroke resulting in weakness of one or both legs; Parkinson's disease; pinched spinal nerves causing pain or affecting walking.
- Musculoskeletal problems: e.g. persistent muscle weakness; muscle wasting conditions; unrepaired hernia; thinning of bone (osteoporosis); previous knee or hip replacement; previous ankle or shoulder surgery; moderate to severe arthritis; routine back or neck pain; previous surgery on the spine; previous knee surgery; knee ligament problems that have not been surgically repaired; fallen arch(es) - flat feet.
- Allergy or sensitivity to the adhesive tape used to affix electrodes

B. Time Requirements

You will be asked to come the lab for two separate sessions, each session lasting up to two hours, for a total of four hours to complete the study.

C. Study Procedures

First Session

On the first day, during the consent process, we will describe what you will be doing in the experiment, show you the equipment you will be wearing, and let you walk on the experimental track. You will undergo a general physical examination by the study physician, to review your health history form, and to assess the flexibility of your joints and range of motion of your limbs. If it is determined that you have any of the exclusionary criteria, or that you have some other pre-existing condition of concern to the physician which would adversely affect the experimental data collection, you will be thanked and excused from the study, and will be provided with $10 compensation for your participation to that point.

If you are accepted into the study and sign the consent form, you will then be given an opportunity to walk around the laboratory wearing the safety harness, to allow familiarization with the equipment (e.g., the harness and fall-arresting rig) and the normal floor surface on the "track". The harness system is designed to protect you during the slip and fall experiments. The fall arresting rig will only allow you to fall 20 cm or less, preventing you from falling to the floor. You may feel a small jerk in your torso as the harness stops your fall. During the first session, you will be assigned to Group A, Group B or Group C. Based on the group assignment, you will perform different activities in the second session.

Second Session
During the second session, you will be asked to change your clothes in a private change room, where you will put on clothes supplied by the lab (e.g., black tank top and shorts). During this session, we will have you wear normal lab supplied shoes (sneakers).

At this time, retro-reflectors (white styrofoam balls similar to ping-pong balls) will be attached, to the laboratory-supplied clothing that you are wearing, over anatomically significant locations on your body, such as your joints. Retro-reflectors will be placed over the joints of the ankle, knee, hip, shoulder, elbow and wrist, as well as on the toes of each foot, calf and thigh of the legs, pelvis, trunk, and head. This will allow us to create computerized stick figure models of your movements during the experiment. To address modesty or cultural concerns, you will be given the choice of having someone of the same gender to affix the retro-reflectors to your garments/body.

We will also attach some electrodes in the calf and thigh muscles of both your legs to record muscle activity. The electrodes are in form of adhesive tape, which can be easily removed. To address modesty or cultural concerns, you will be given the choice of having someone of the same gender to affix the electrodes. We will ask you which of your feet is your dominant ("kicking") foot.

1. First Experimental Component - Baseline
Wearing the normal lab shoes, you will be asked to walk back and forth along the test "track" for 10 minutes. At both ends of the track, there will be a station where you will receive written instructions directing you to perform specified filing tasks, e.g., separate 4 blue pieces of paper and file them. You will also receive written instructions to look at the TV screen at the opposite end of the track, as you are walking to that end, to count the number of dots on the screen of a certain color. When you reach that end of the track, you will be asked to tell how many you observed. You may be supplied with a Walkman audio player during the walking experiment, playing old comedy routines, to conceal any noises associated with laboratory activities. If you become tired during walking, please let the lab staff know that you would like to stop and rest. If you wish to withdraw from the study, you may do so.

2. Second Experimental Component – Training
If you are assigned to Group A, B, or C, please read the appropriate paragraph below corresponding to your assigned group -- A, B, or C

A. Group A: During the next 30 minutes, you will keep walking on the track and at random intervals, the researchers may or may not induce simulated slips on the track (by a moveable platform). You may or may not slip but the harness will protect you in case you do. You will be asked to maintain balance and continue walking even after you experience a slip. You will go through 10-15 trials of the simulated slips. Please let the lab staff know if you would like to stop and rest at any point or if you wish to withdraw from the study, you may request to do so.

If you choose not to continue on to the next session on this day, you will, at the conclusion of the test, change back into your personal clothes, and will be paid for your participation in this session. If you decide, and are permitted to continue on to the next session on the same day, you will remain in the lab supplied garments with the retro-reflectors and electrodes attached.

B. Group B: During the next 30 minutes, you will be asked to walk on a treadmill in a comfortable speed. You will be provided with a harness even when you are walking on the treadmill. After walking for 5 minutes and getting used to the treadmill, you will be asked to wear a visual display. This display will consist of a virtual scene of a regular street. As you walk on the treadmill, you will have a sense of walking in the virtual environment. After walking for 5-10 minutes, you will be exposed to a visual tilt that may or may not induce some balance loss. If you slip, the harness will protect you from falling. You will be asked to try to keep your balance while walking on the treadmill. If the visual scene is making you dizzy, please let the lab staffs know that you would like to stop. You will go through 10-15 trials of visual tilts. Please let the lab staff know if you would like to stop at any point and rest or if you wish to withdraw from the study, you may request to do so.

If you choose not to continue on to the next session on this day, you will, at the conclusion of the test, change back into your personal clothes, and will be paid for your participation in this session. If you decide, and are permitted to continue on to the next session on the same day, you will remain in the lab supplied garments with the retro-reflectors and electrodes attached.

C. Group C: During the next 30 minutes, you will be first asked to walk on the track at a comfortable speed. After walking on the track for 10 minutes, you will be asked to walk on the treadmill at a speed of 2.0mph for 10 minutes. After completing the treadmill walking, you will be brought back to the track and would be asked to walk at your comfortable speed for another 5 minutes. Please let the lab staff know if you would like to stop at any point and rest or if you wish to withdraw from the study, you may request to do so.

If you choose not to continue on to the next session on this day, you will, at the conclusion of the test, change back into your personal clothes, and will be paid for your participation in this session. If you decide, and are permitted to continue on to the next session on the same day, you will remain in the lab supplied garments with the retro-reflectors and EMG electrodes attached.

3. Third Experimental Component – Slippery Conditions

All of the groups (A, B and C) will perform this section. During the next 15 minute session, you will conduct similar filing tasks as described in the "First Experimental Component-Baseline" section above. At one random time point, the researchers will, without your knowledge, create a slippery condition on the track. You will slip, but as mentioned previously, the harness will prevent you from falling on the floor. You may experience a jerk in the shoulders and neck as the harness prevents your fall. If you become tired during walking, please let the lab staffs know that you would like to stop and rest. If you wish to withdraw from the study, you may request to do so.

At the conclusion of this session, you will change back into your personal clothes, and will be paid for your participation in this session.

At least two graduate research assistants will be present during all testing periods. Staff members running the tests will strongly emphasize, in both spoken and written instructions, that you are free to discontinue participation at any time. All lab-supplied garments that you will wear will be laundered after each use, with all subjects provided with clean, laundered garments.

III. Risks Involved in Participation

While this study involves the use of safety equipment to prevent contact with the floor during an experimentally induced slip or fall, it does involve more than minimal risk for individuals with bone, joint, or muscle problems. For that reason, individuals with any of the exclusionary criteria have been excluded from the study.

You might encounter the following risks during your participation:
Emotional – You may feel disappointment or self-doubt in not being as agile as when you were at a younger age. You may feel embarrassed at what you perceive as a "poor performance".
Physical – You could experience minor muscle sprain (similar to those encountered in regular daily activities), joint pain (shoulder, knee, ankle), or neck sprain. To minimize injuries, you will be wearing a fall arresting rig and harness system to protect you from any harm caused by slips and falls. Prior to your participation, the harness system will be adjusted to your individual height, ensuring that falls are limited to 7 inches or less limiting the downward and forward progression of your body to reduce physical risks noted above. The experiment will be terminated if one of the following conditions occurs: if you decide to discontinue participation; or, you experience any pain in the back, knees or ankles following walking or slipping. Potential participants will be excluded if bone or joint problems are present that would make participation unsafe or which would compromise the integrity of the research results.

Over 120 human subjects have been tested using the walking surfaces and safety harness, and to date, no injuries have occurred. However, in the event that you are injured while participating in the study, you will be responsible for any expense associated with emergency medical treatment, as neither the researchers nor the University have money set aside for medical treatment expenses.

IV. Benefits from Participation
You are not promised any specific/direct benefits for your participation in this study. The results of this study may yield benefits to adults and seniors through development of training paradigms for fall prevention.

V. Extent of Anonymity and Confidentiality
You will be assigned a unique individual code number. The code number will be used on all of your study documents and data files. The Principal Investigator (PI), Dr. Lockhart, will maintain a code key list to link your personal information to the code number used on your data. The code key list will be kept locked in a filing cabinet in the PI's office, and will not be accessible to anyone who is not a project staff member. Coded data will be stored on a computer with password-protected access, and hard copies of data will be kept in a locked filing cabinet in the lab or in the PI's office. At the conclusion of the study, the data will be analyzed, and will be published in scientific journals. You will not be identified in the publications, and your anonymity and confidentiality will be maintained. As required by federal law and Virginia Tech IRB Policy, study records will be maintained for 3 years after the conclusion of the study, after which time they will be destroyed.

Your movements will be monitored/recorded by an infrared camera used to detect movements of the retro-reflectors, so that we can create computerized stick figure models of your movements during the experiment. The camera will not yield images from which your likeness would be identified, only the highlighted white retro-reflectors.

VI. Compensation
Participants enrolled in the study will receive $20 per session in the lab. You will spend two sessions (2 hours each) in the lab, for a total compensation of $40. Compensation will be pro-rated, that is if you withdraw during the first session, you will be compensated $10. If you withdraw during the second session, you will be compensated $20 for partial completion of the study.

VII. Freedom to Withdraw
You are free to withdraw from the study at any time and for any reason. Should the researchers determine that you should be removed from the study, you will be thanked and excused, and provided with pro-rated compensation.

VIII. Subject Responsibilities
You are expected to provide accurate information on your Medical History form. You are expected to adhere to your scheduled participation dates, advising the PI if the date(s) need to be rescheduled, unless you decide to withdraw from the study.

IX. IRB Review of Research
The Virginia Tech Institutional Review Board (IRB) for Projects Involving Human Subjects, has reviewed this proposed study, and has determined that it is in compliance with federal laws and Virginia Tech policies governing the protection of human subjects in research. However, you should recognize that the review does not constitute an endorsement of the research, and that it is

up to you to determine whether you are willing to participate in the study after having been informed of the risks, benefits, and procedures involved in this study.

X. Subject / Participant's Permission

I have read the Consent Form and conditions of this project and have discussed it with the research staff or PI. I have had all my questions answered to my satisfaction. I hereby acknowledge the above and give my voluntary consent to participate in this study:

____ Date__________

Subject's Signature

Subject's Project Identification Code: _____________

Should you have any questions about this research or its conduct, research subjects' rights, and whom to contact in the event of a research-related injury to the subject, you may contact:

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NOTE:

- You must be given a complete copy (or duplicate original) of the signed Consent Document.
- This Consent document must bear an official IRB date stamp.